NEWNES' "ELECTRICAL ENGINEER" SERIES

General Editor: E. MOLLOY

UNIFORM WITH THIS VOLUME

No. 1. *Electric Wiring: (Domestic)*
,, 2. *Practical Design of Small Motors and Transformers*
,, 3. *Installation and Maintenance of Electric Motors*
,, 4. *House Telephones, Bells and Signalling Systems*
,, 5. *Wiring Circuits for Lighting, Power and Industrial Control*
,, 6. *Testing Electrical Installations and Machines*
,, 7. *Factory Installation Work*
,, 8. *A C. Motors and Control Gear*
,, 9. *Switchboard Instruments*
,, 10. *Cables and Wires: Selection, Jointing and Testing*
,, 11. *Power Transformers*
,, 12. *Electro-Plating and Anodising*
,, 13. *Power Rectifiers*
,, 14. *Electric Lifts*
,, 15. *Private Generating Plant*
,, 16. *Electric Relays*
,, 17. *Physics for Engineers*
,, 18. 101 *Electrical Examination Questions. With Model Answers*
,, 19. *Mathematics for Engineers*
,, 20. *Introduction to Electricity and Radio*
,, 22. *Mechanics for Engineers*
,, 23. *Diesel Electric Shunting Locomotives*
,, 24. *Electronic Developments*

Each 7/6 net

INTRODUCTION TO ELECTRICITY AND RADIO

BY

T. H. TURNEY, Ph.D.

LONDON
GEORGE NEWNES LIMITED
TOWER HOUSE, SOUTHAMPTON STREET
STRAND, W.C.2

First published	. . .	*1943*
Second Edition	. . .	*1946*
Third Edition	. . .	*1948*

PREFACE TO THIRD EDITION

A FEW remarks have been added to emphasise what is more important in the early pages dealing with principles.

Chapters have been added on Negative Resistance and Negative Inductance and on "Pictorial" Radiolocation. This phrase describes the newer inventions in that field.

T. H. T.

PREFACE TO SECOND EDITION

IN preparing this second edition, the opportunity has been taken to incorporate some additional information which the reader should find of considerable interest. In the Introductory Chapter the "Magnetic Effect of Electric Current" has been made a sub-section.

"Pulse Time Modulation" and the "Characteristic Impedance of a Filter", are other features of the new edition, and four completely new chapters dealing respectively with the "Co-Axial Cable," "Heterodyne Receivers," "Maxwell's Curl Equations," and "Wave Guides," have also been included.

T. H. T.

PREFACE

INTRODUCTION TO ELECTRICITY AND RADIO has evolved out of two lecture courses which I undertook in Liverpool, the one on the fundamentals of electrical science to the junior members of the staff of the Automatic Telephone

Mfg. Co., Ltd., and the other, on radio, to students in the Royal Air Force.

My aim has been to give students of radio a thorough knowledge of their subject, not only as regards the important details but in broad fundamentals. So that when they have read and studied its pages they will never be in danger of becoming lost in a mass of details because they can at any time retrace their steps from first principles. As every experienced teacher knows the stimulus that he himself gets from helping the enquiring, intelligent student to solve his difficulties results in clarification of his own mental processes. I sincerely hope that I have succeeded in transferring to these pages the results of this mutually helpful process and that *Introduction to Electricity and Radio* will be of use to those for whom it has been written.

Without allowing colloquialisms and technical phrases to become a cloak for avoiding difficulties I have tried to talk to students in the language they use and understand. If on the basis of the book they are able—and experience tells me that the hope is not without justification—to give clear and understandable explanations of the terms they use and the circuits they elaborate, then my aim will have been realised.

My thanks are due to the Automatic Telephone Mfg. Co., Ltd., for permission to make use of the lectures which I delivered to their staff; to my friends and colleagues Messrs. Peover, Ireland and Spearman for help with the illustrations; to Mr. K. E. Clifton for encouragement at all times and to Mr. D. Woolven for stimulating discussion which clarified my own thoughts and helped me to write, I hope, with simplicity and lucidity.

T. H. T.

CONTENTS

CHAPTER I

INTRODUCTORY

LIKE the student who, when asked to define "work" in mechanics said "Everything is work," so we may say that electricity is the stuff everything is made of. Every atom of every substance has one or more electrons or particles of electricity. These may be rubbed off, just as dust is rubbed off one's coat. For example, if a fountain-pen is rubbed on a coat sleeve it becomes electrified and will pick up bits of paper or straw. When two substances are thus rubbed, one loses electrons and the other gains them. The one that loses them is said to be positively charged, the other negatively. The rubbing of amber and the property it acquires of attracting and holding light objects such as small pieces of paper, has been known for ages. Another property of another substance found in a natural state has been known since ancient times. This time it is magnetism which is involved and the natural substance not amber but an oxide of iron. The ancients used "lodestone" suspended by a thread as a compass to point north and south when crossing the desert. These two properties—that of amber to attract light objects when rubbed and of lodestone to point always to the north when suspended by a thread—seemed to have no connection, and it was not until the middle of the nineteenth century that any connection between them was recognised, when Michael Faraday showed that there was in fact a very close connection.

We have said that *everything*—a table, a piece of iron or copper, the rocks and trees—all have countless *electrons* in them. When the electrons in a wire are made to move along it, we say there is an *electric current* flowing in the wire, just as currents flow in air or water. We may have a room in which there seems to be no air. The air is there, but it

is not in motion; there is no breeze, no flow, no current. A fan or a pump, for circulating the cooling water in a motor car, causes a current to flow. So the battery or dynamo acts like a *pump* and drives a current of electrons or electricity round the circuit.

Take a torch as a simple example. Here the electrons leave the battery at the point where the coiled spring is. They flow through the coiled spring itself, up the case towards the bulb, then into the bulb when the switch makes contact, through the wire or filament which gives the light and out of the bulb into the battery through the little spot of solder on the bulb.

When contact is *broken* at the switch, current *ceases to flow* because electrons will not flow through air, at least not at the low pressure or voltage of a torch battery.

With thousands of volts, however, current *will* flow in air and give a spark. This is lightning flash in miniature.

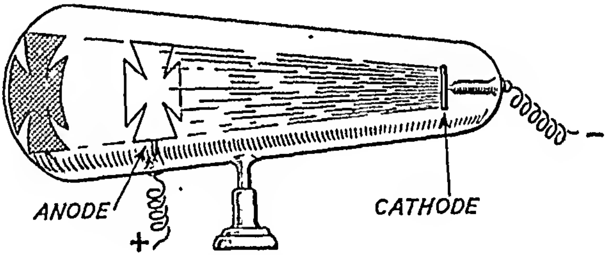


FIG. 1.—ELECTRONS FLOWING IN A VACUUM.

One beautiful experiment shows the flow of electrons in a vacuum. A pear-shaped glass tube has a piece of wire sealed into it at one end, and another wire connected to a metal cross sealed in near the other end. (Fig. 1).

When a high pressure is applied to the two wires, the first piece of wire being connected to the negative of the coil supplying the current, a stream of electrons flows along the tube. Some hit the cross, but not all; others go past its edges, and strike the end of the glass tube. The glass is a special

glass, which glows green when electrons hit it. The result is a vivid green glow on the end of the glass tube, with a dark shadow shaped like a cross where the cross intercepts the flying electrons. Those electrons which hit the cross return to the coil which acts as a pump like a battery.

About 200 large H.T. batteries would do instead of the coil! The coil was invented first, and is cheaper.

Here electrons are given off by a cold piece of metal wire. If that wire is hot as in a radio valve, much less voltage is needed. Thus the high tension voltage for a valve may be as low as 10 volts.

There are two effects of electricity. Like wind, electricity is known by its effects. If we see the smoke from chimneys blowing up the road we say: "It is a south wind." So with electricity. When the heat is there, we know the current is "on". In addition to the glowing of a torch-bulb, and the glow of the glass of the Crookes tube, there are other effects.

The chief effects of the electric current are:

1. The Generation of Heat.
2. Production of Magnetism.
3. Chemical breaking down.
4. Induced Voltage caused by variable currents.

Heating Effect of the Electric Current.

Whenever a current flows through a conductor, heat is generated. Current flows more easily through some metals than others, and scarcely flows at all through such substances as rubber or glass. These are called insulators and the metals together with carbon, are called conductors.

Conductors are always heated by the passage of a current through them and for a given current the poorer the conductor the greater the heat developed. This is the principle of the electric fire, and toaster. The heating wires are made of a poorly conducting metal. They become hot, although the wires leading from the plug, being made of copper, a good conductor, keep cool.

Magnetic Effect of a Current.

A moving electron produces a magnetic field in the space round about its path, which is the same as saying that a

in this way, there is an important difference between the two. On removing the metal from the coil or on turning the current off, a piece of iron will lose its magnetism while steel will retain it. This is thought to be chiefly due to the difference in hardness between the two. The theory is that every molecule of a piece of iron or steel is in itself a complete magnet. In an unmagnetised bar, the molecules are arranged higgledy-piggledy, so that there is no resultant magnetism, but when a piece of metal is magnetised, all the molecules turn round and face one way. In the case of soft iron, the molecules are free to turn back again when the magnetising force is removed. In steel, however, the molecules are not free to turn back and the steel remains magnetised.

Magnetic Fluxes.

Magnetic Fluxes, like electric currents, always exist in circuits or closed loops like elastic bands.

Three important points should be remembered about magnetic lines of flux.

(1) Lines object to crowding.
(2) They like to take the shortest path.
(3) They never cut each other.

The lines of flux in a magnet may be imagined to enter at one end, the South Pole, and leave at the other, the North.

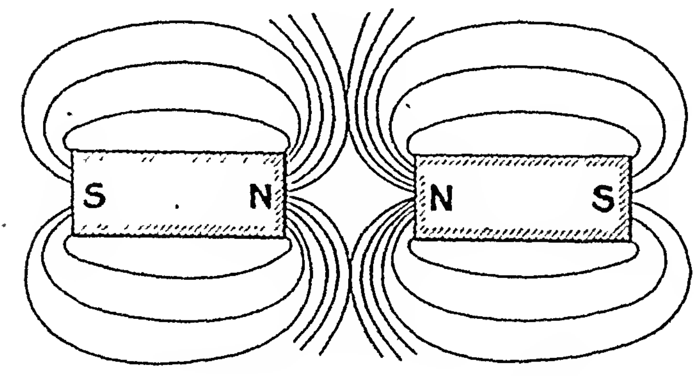


FIG. 2a.—LIKE POLES REPEL EACH OTHER.

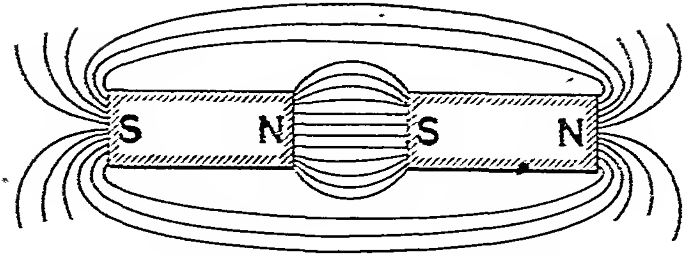


FIG. 2b.—UNLIKE POLES ATTRACT EACH OTHER.

It is found that a trace of cobalt in the steel helps it to retain its magnetism; indeed, some of the new special steels are remarkable for their magnetic properties.

As the lines of flux radiating from a magnet can never cut each other, a North pole will repel another North pole brought near (Fig. 2a). On the other hand, when a North pole is brought near to a South pole, the lines take the form shown above, and the two unlike poles attract (Fig. 2b).

THE MAGNETIC EFFECT OF ELECTRIC CURRENT

One of the very important facts about an electric current is that it *always produces magnetic flux.* If we wind wire round a piece of iron, such as an iron nail, and send a current round the turns of the wire, then the nail becomes magnetic and will pick up small pieces of iron. Powerful magnets can be made in this way.

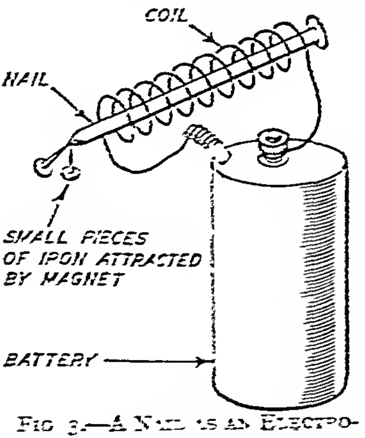


FIG. 3.—A NAIL AS AN ELECTRO-MAGNET.

Even a single straight wire causes a flux. In this case the magnetic flux is in circles round the wire. Strictly speaking the current causes a Magnetic Force and this force causes the flux. For a given Magnetic Force the flux is

larger if an iron path, like the nail is provided, than in the case of an air path. Many turns are needed round the nail to make a good magnet.

The general rule however is always true:

Current Causes Magnetic Flux. This is one of the chief things which has been discovered in nature, where physics is concerned. See Fig. 3.. The wire should be insulated to make the current go round the turns and not jump from one to the next.

Here is a simple experiment. Take a loop of wire and send a current up one side and down the other. There will then be a field round the "up" wire in one direction and a field round the "down" wire in the opposite direction. These two fields repel each other and the wires tend to fly apart when the current is switched on. The field round a straight wire is circular and the field is strongest close to the wire.

Let us take two circles, one of 1 in. and the other of 2 in. radius, surrounding a wire. How strong is the flux in the inner circle compared with that in the outer circle? It is the same current which produces both fluxes, and therefore as the flux line is twice as *long* in the case of the outer circle it will have only half the strength. We thus conclude that in the case of a straight wire carrying a current, the flux density outside the wire is inversely proportional to the distance from the centre of the wire.

It cannot be too strongly emphasised that fluxes are directional, i.e. they are "vectors". A vector is a quantity which has direction as well as magnitude. *Force, velocity, acceleration, magnetic flux—all these are vectors.*

If we have a ship steaming North at 8 miles per hour and a man is crossing the deck from East to West at 6 miles per hour, the true speed of the man relative to the water will be 10 miles per hour. This is found by drawing a parallelogram of velocities as shown in Fig. 4.

Sine waves are often thought of as being produced by rotating lines. These are like vectors, and they add like vectors. A sine wave is not a true vector because it has no direction in space. But sine waves add like vectors so the moving line is often called a vector.

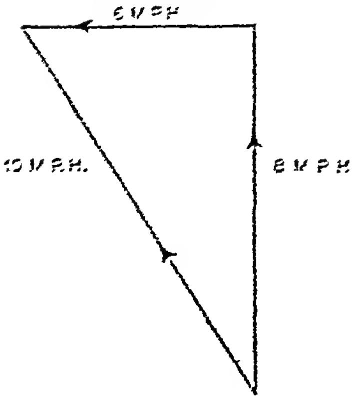


FIG. 4.—TRIANGLE OF VELOCITIES.

Batteries.

All the early work on electricity was done with batteries and there are two or three types still in use. One is the type used for torches and High Tension Batteries. Each cell has a zinc case which is part of the cell, a carbon rod in the middle and a paste containing sal-ammoniac among other things. When the zinc is eaten away by the passage of the current which the battery generates, then the cell is run down. New types lately invented are made in layers and are not cylindrical unless one calls a pancake a cylinder. They are like a sandwich.

When the carbon of one cell is connected by a wire or made to touch the zinc of another as in a two cell torch, then the cells are said to be in series, as in Fig. 5.

Then the voltages of the cells all add up and if the voltage of each cell is $1\frac{1}{2}$ the total voltage is 6. If the cells are connected as in Fig 6, the cells are said to be in parallel.

When the cells are in parallel their voltages do not add up. The pressure or voltage on the lamp is still $1\frac{1}{2}$ volts, the same as that of a single cell, but the currents from the cells add up to form the total current through the lamp. We have then a most fundamental rule:

IN SERIES . . ADD VOLTAGES.
IN PARALLEL . ADD CURRENTS.

In practical experiments it is found that the resistance in each cell uses up a part of the pressure in order to drive the current through the cell on its way to the lamp. The main thing, however, is that *the pressure measured in VOLTS causes a current measured in AMPERES to flow through the lamp.*

Accumulators.

An accumulator is a battery which can be recharged,

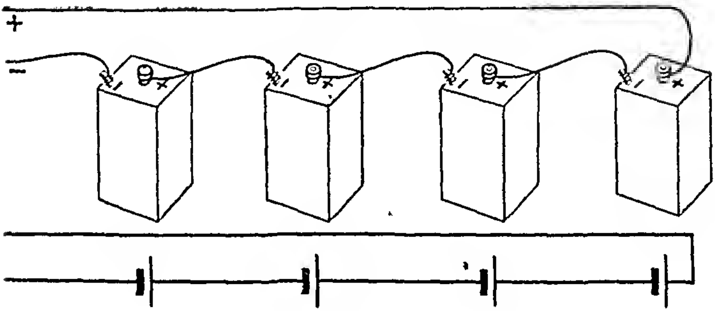


FIG. 5.—BATTERIES IN SERIES.

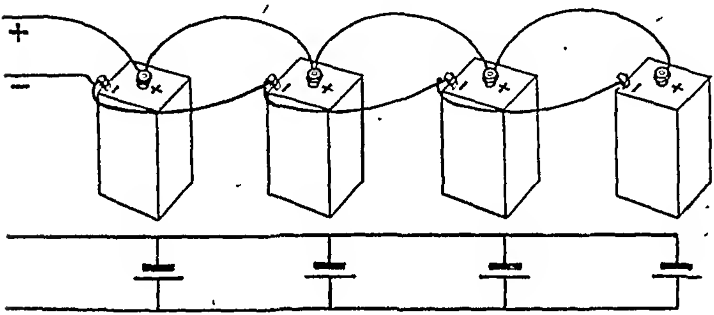


FIG. 6.—BATTERIES IN PARALLEL.

when run down, by passing a current through it from another battery or dynamo in the reverse direction. The torch type of battery gets weak towards the end of its life but a lead-acid accumulator does not, and it can be charged-up very easily as just described.

There are three signs which tell when the recharging is complete and the accumulator again up to full strength.

(*a*) The positive plates look dark-chocolate in colour.
(*b*) The acid gives off gas and bubbles rise to the surface.
(*c*) The acid density rises.

Having dealt with batteries and said that currents flow in circuits, we now proceed to describe how currents are measured. Really one of the *effects* is measured.

CHAPTER II

ELECTRIC CURRENT MEASUREMENT

WE have spoken of electrons as small particles of electricity, and now we have to consider electrons in motion, i.e. an electric current. A current of electricity like a current of air or water, is merely a flow. There are two things of importance in a flow, the first is the *direction* of flow and the second is the *rate* of flow. The actual velocity of flow is unimportant.

By rate of flow, we mean the number of electrons per second, just as we speak of the number of gallons per second passing a given point in a stream. For power purposes the direction and the rate of flow are very important, and it is equally so in the case of electricity. What then do we use in electricity as a measure of quantity of electricity? What *unit of measurement* do we use in electricity corresponding to our gallon in measuring water? The electrical unit of quantity is the Coulomb and it consists of 9×10^{18} electrons.

This rate of flow is so important that there is a special name for it. A flow of *One Coulomb per second is called an ampere*, after the scientist Ampère.

When an electric current is flowing through a heater, the greater the flow in amperes the greater the heat produced, and when a current is flowing through a lamp, the more amperes, the brighter the light.

Let us now consider how amperes are measured. There are two main types of meter for measuring electric current, one depending on the heating effect of a current, the other on its magnetic effect. A meter which depends on the heating and expansion of a wire is called a "Hot Wire" instrument.

Hot Wire Ammeter.

In this instrument a fine wire is stretched between two screws inside a draught-proof case. To the middle of this wire is connected another as shown in Fig. 7. To this second wire

a thread is attached, which passes over a pulley connected to the pointer. As the current to be measured heats the first wire it expands and sags by a definite amount corresponding to the current flowing. This movement is transmitted to the pointer, thus giving an indication of the current flow through the instrument.

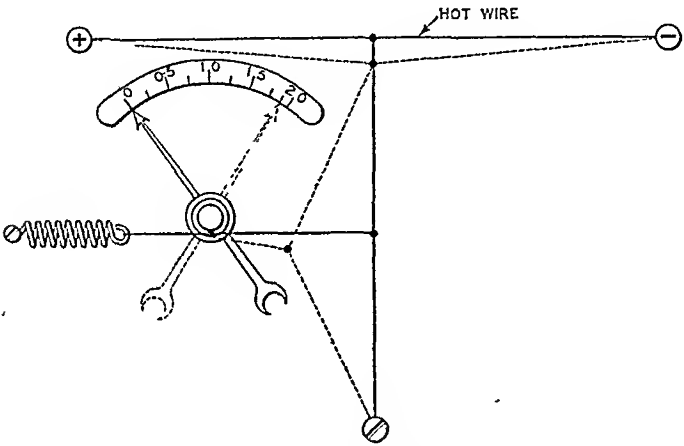


FIG. 7.—HOT WIRE AMMETER.

The instrument has the disadvantage that its deflection is proportional to the square of the current, and thus the deflection of the pointer for 7 amperes is 49 times the deflection for one ampere. The heating effect of a current is always proportional to the square of the current in amperes. It looks therefore, as though, if we have a current of say 3 amperes in a heater and then increase the flow by 3 more amperes, that we are getting something for nothing. The fallacy will be seen later when we consider power and electrical pressure.

Tangent Galvanometer

Another very simple instrument for measuring current is known as the Tangent Galvanometer. This depends on the deflection of a magnet by an electric current.

If we observe θ, in degrees, the proportion of the sides CB to CA follows at once. In trigonometry we say

$$\text{Tan } \theta = \frac{CB}{CA}$$

Tan θ is simply the name given to a particular value of the ratio $\frac{CB}{CA}$ for a particular value of the angle θ.

Here is a table of the values of tan θ for ten values of θ.

$\theta°$	Tan θ
0	0
10	·176
20	·364
30	·577
40	·839
50	1·19
60	1·73
70	2·75
80	5·67
90	Infinite

We have then $\frac{kI}{H} = \tan \theta$.

Now as the earth's field is constant, it follows that H as well as k is a constant. Thus the *current I is proportional to the tangent of the angle θ.*

Magnetic Instruments.

A very good type of instrument for measuring amperes depends on the magnetic effect of a current, and is called a moving-coil ammeter.

If a wire carrying an electric current is placed in a magnetic field, the wire experiences a force tending to move it at right angles to the flux—not towards the magnet or away from it but at right angles to the flux. This may be memorised

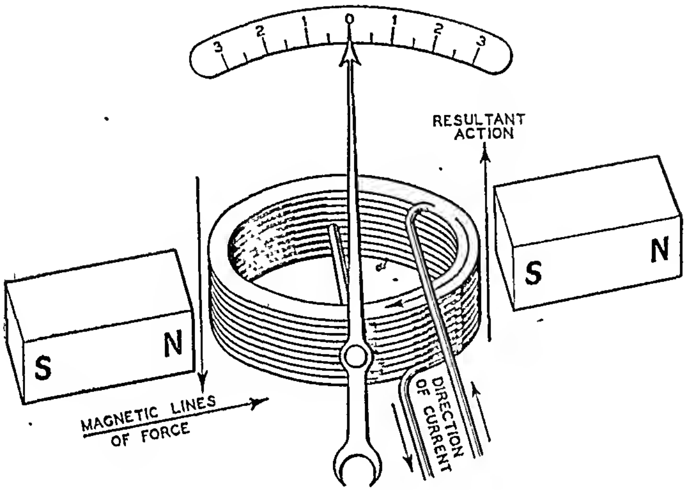


Fig. 9.—Construction of Moving Coil Ammeter.

by what is known as the left hand rule. If the thumb, forefinger, and second or index finger be held at right angles to each other, the following relations apply.

If the forefinger represents the direction of the flux, and the index finger the direction of the current, the thumb will indicate the direction of motion of the wire. The working may be shown by taking two magnets and a suspended coil of wire. The magnets are arranged North to South to send a flux past the coil, which is free to turn about a vertical axis. If we send a current round the coil, it will go along one side and back along the other. (See Fig. 9).

Applying the left hand rule it will be found that one side of the coil tends to move backwards and the other forwards. Consequently the coil twists as a whole. This is also the principle of an electric motor, which has two chief parts, a stationary frame with field magnets and a moving armature carrying coils of wire. As each coil on the armature moves a little way, the current is switched on to another coil by a special rotating switch known as the commutator.

Electric Pressure.

In addition to current strength, it is necessary to consider pressure. This will be seen from a consideration of waterfalls. A shallow fall such as the Horseshoe Falls at Llangollen, having a height of about 3 feet, will not be as powerfui, gallon for gallon, as say Aira Force in the Lake District, which has a height of about 80 feet. The difference is in the pressure. Electrical pressure is measured in volts and the following list gives an idea of the size of a volt.

Pocket lamp battery . .	$1\frac{1}{2}$—$4\frac{1}{2}$ volts.
Telephone Exchanges . .	20—60 volts.
Electric supply for houses .	115—230 volts.
Trams	500 volts.
Trains	600 volts upwards.
Lightning	Several million volts.

We have seen how an ammeter works. How does a voltmeter work? The voltmeter is an instrument designed to measure pressure.

The Voltmeter.

How do we determine the pressure in a water pipe? The simplest way is to take a fine drill and bore a small hole in the pipe. If the water comes out slowly we know that the pressure is low. If however, it comes out fast, we know that there is a high pressure in the pipe.

A voltmeter is designed to do the same for electricity. It is an instrument which measures the current flowing through a small "leak" in the circuit. This leak usually consists of a high resistance placed in the instrument case.

In using meters it is important for the beginner to note that if we wish to measure the pressure which is being applied to a piece of apparatus, the voltmeter should be placed across the apparatus, owing to its high resistance. An ammeter, on the other hand, should be placed in *series* with the apparatus so that the current to be measured may actually flow through the instrument.

Electrostatic Voltmeter.

There is a type of voltmeter which does not measure the current through a leak, but measures pressure directly.

If two insulated plates are connected to the two poles of a battery, one will be charged negatively and the other positively, i.e. one plate has an excess and the other a deficit of electrons. These two plates will then attract each other with a real mechanical force. This force is slight but by allowing the plates to move freely under the influence of a very light spring, the electric pressure or voltage which is tending to move them, can be measured.

Electric Power.

The power of a current depends on the pressure and on the current flow. It is therefore necessary to multiply volts by amps. to get power. Power is measured in watts. One ampere at a pressure of one volt is one watt.

$$\text{Pressure} \times \text{Current} = \text{Power}$$
$$V \times I = W$$

Thus an electric iron working on a 200-volt circuit taking 2 amperes consumes 400 watts.

CHAPTER III

OHM'S LAW.

WE have spoken of the current flow in amperes and also of the pressure in volts. We have now to ask what determines the amount of current flowing in any circuit. The answer is to be found in the resistance which conductors offer to the passage of an electric current. A thin wire naturally offers a higher resistance than a thick one. An iron wire offers more resistance than copper wire of the same form, and so on.

The pressure in volts drives the current in amperes through the resistance, which is measured in ohms How big then is an ohm? An ohm is a resistance of such a size that a volt will drive one ampere through it. Similarly.

2	volts	drive	2	amperes	through	1 ohm.
2	,,	,,	1	,,	,,	2 ,,
4	,,	,,	2	,,	,,	2 ,,
8	,,	,,	4	,,	,,	2 ,,
6	,,	,,	2	,,	,,	3 ,,

In order to obtain the current, then, we divide the volts by the ohms.

$$\text{Amps} = \frac{\text{volts}}{\text{ohms}}$$

It is customary to use I for current, E for volts and R for ohms. E is used as short for e.m.f. which means electromotive force.

We have then, in symbols, $I = \dfrac{E}{R}$

By algebra, this can be changed to $IR = E$
and in this form the formula is useful when we know the resistance R and current I and we wish to find the pressure E.

Again, the law may be written $R = \frac{E}{I}$ in which form it is possible to calculate the resistance from the pressure and the current.

Wide Application of Ohm's Law.

Ohm's Law is of universal application; it is true for the whole circuit, and for every part of it taken separately, and for any two or three parts of a circuit taken together.

Example 1. A lamp is fed from a 100 volt dynamo over a cable whose resistance is 5 ohms. The current going out, measured on an ammeter is ½ an ampere. Find (a) The resistance of the lamp. (b) The voltage on the lamp. (c) The volts lost on the cable.

The whole point of this problem is that the pressure from the dynamo has to force the current of ½ ampere along the cable and through the lamp. We know the cable resistance but do not know the lamp resistance. We can however find the total resistance for the circuit from the known current of ½ ampere and the known voltage 100, thus:

$$R = \frac{E}{I} = \frac{100}{\frac{1}{2}} = 200 \text{ ohms.}$$

As the resistance of the cable is 5 ohms, the lamp resistance will be 195 ohms.

Now apply ohm's law to the lamp.

$$E = RI.$$

$E = 195 \times \frac{1}{2} = 97\frac{1}{2}$ volts for the voltage on the lamp. The other $2\frac{1}{2}$ volts represent the loss in the cable.

We may now see why the heating effect of a current is proportional to the square of the current.

Heat is a form of energy and therefore the *rate* of production of heat is equal to the rate of waste of electrical energy which is power in watts. Power is the rate of expending energy.

Power in watts $= E \times I$ but from Ohm's Law $E = RI$.

Thus $W = RI \times I = RI^2$.

The reason why a double current through a wire represents four times the power is that in order to double the current, it is necessary to double the pressure in order to force the double current through the same resistance.

Resistances in Series.

Take two resistances in series, and call them R_1 and R_2. (Fig. 10). What will be their combined resistance?

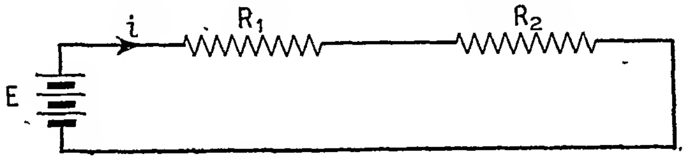


FIG. 10.—RESISTANCES IN SERIES.

Let the current flowing from a battery of E volts be i amperes.

Now apply Ohm's Law to each resistance separately thus:

$$\begin{aligned} &\text{Voltage } e_1 \text{ on } R_1 &&= R_1 i \\ &\text{Voltage } e_2 \text{ on } R_2 &&= R_2 i \\ &\text{Total voltage } E &&= (R_1 + R_2)i. \end{aligned}$$

Now divide E by i to get the total resistance and $\frac{E}{i} = R_1 + R_2$. *Thus Resistances in series add up.*

Resistances in Parallel.

Here, let the battery once again have a voltage E. The current through R_1 will be

$$i_1 = \frac{E}{R_1}$$

Similarly $$i_2 = \frac{E}{R_2}$$

$$\text{Total } i = i_1 + i_2 = \frac{E}{R_1} + \frac{E}{R_2}$$

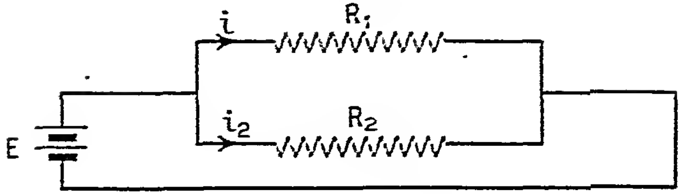


FIG. 11.—RESISTANCES IN PARALLEL.

$$i = E\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Now to find the total resistance, divide E by i and we have

$$\frac{E}{i} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

If we call R_T the total resistance, we have

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$$

We cannot say that resistances in parallel add up, but we can say that their reciprocals add up to the reciprocal of the total resistance. After a few trials it will be seen that the total resistance of a number in parallel is smaller than the smallest one in the group. Applying these rules again and again, it is possible to determine the currents in all branches of a network however complicated it may be.

Where there are only two resistances in parallel

$$R_T \text{ is } \frac{R_1 R_2}{R_1 + R_2} \text{ or } \frac{\text{Product}}{\text{Sum}}$$

6 ohms and 12 ohms in parallel would be 3 ohms.

Linear Nature of Electrical Quantities.

In the experiment illustrated above, doubling the voltage doubles the current according to Ohm's Law. But whilst it is a very convenient method of calculating current, Ohm's Law is much more than that, and has other far-reaching consequences.

If Ohm's Law stated that the current was proportional to the square of the voltage or something of that sort, what follows would not be true. It is the simple proportionality which counts. If now we have two batteries in a circuit either at the same place or at two different places, the current everywhere in the circuit may be found by calculating that due to each battery separately and adding the results. This process holds in the case of all electrical pressures, whether alternating or direct.

Mathematicians, used to plotting graphs, call Ohm's Law a "linear law" because anything which is in simple proportion.gives a straight line when plotted on a graph.

In order to get a working knowledge of electricity it is essential to remember what volts, amps. and ohms mean and how easy calculations are made. A few examples will help.

Problems of Ohm's Law.

Let us find the answer to a series of problems concerning the current flow through circuits. All yield to Ohm's Law. It cannot be too clearly grasped that Ohm's Law can be used several times in the same circuit, each time in one of its three forms.

(1) Given a Resistance and a Voltage, to find a Current use the formula $I = \frac{E}{R}$

(2) Given a Current and a Resistance, to find a Voltage, use the formula $E = RI$

(3) Given a Voltage and a Current, to find a Resistance, use the formula $R = \frac{E}{I}$

Of course it is the same formula every time, but turned round to suit the purpose. There is one way, and only one way to grasp Ohm's Law and that is to turn it over in one's mind and try problem after problem. To solve problems out of a book is good, but it involves looking at the book, and there is a better way; that is to make the problems up for oneself. A young student who does that is just as well

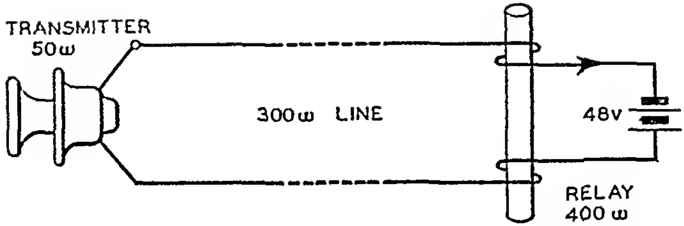


FIG. 12.—IMPULSE RELAY IN CIRCUIT WITH TELEPHONE TRANSMITTER.

$$\text{Total resistance} = 400 + 300 + 50 = 750$$

$$\text{Current } I = \frac{E}{R} = \frac{48}{750} = \frac{16}{250} = \cdot064 \text{ amps.}$$

(1) The Transmitter voltage is given by applying Ohm's Law to the Transmitter:

$$E = RI = 50 \times \cdot064 = 3\cdot2 \text{ volts.}$$

(2) The power loss in the relay coils is given by

$$W = RI^2$$
$$= 400 \times (\cdot064)^2 = 1\cdot62 \text{ watts.}$$

Example 4. Two lamps are lighted in parallel from a 240 volt circuit. One is a 30 and the other a 60 watt lamp. Find the total resistance of the two lamps in parallel.

Method.

Find the current in each lamp, and as they are in parallel, add the currents together.

$$\text{Watts} = \text{Volts} \times \text{Amps.}$$
$$30 = 240 \times i_1$$
$$i_1 = \cdot125 \text{ amps.}$$
$$\text{Again } 60 = 240 \times i_2$$
$$i_2 = \cdot25 \text{ amps.}$$
$$i_1 + i_2 = \cdot375 \text{ amps.}$$

Now R is given by $R = \frac{E}{I}$ so

$$R = \frac{240}{\cdot375} = 640 \text{ ohms.}$$

There is another way to do this problem and it brings in the formula for resistances in parallel.

First find the resistance of each lamp and then combine the two.

Current for 1st lamp = ·125 amp.

$$\text{Resistance} = \frac{240}{\cdot 125} = 1920 \text{ ohms.}$$

Current for 2nd lamp = ·25 amp.

$$\text{Resistance} = \frac{240}{\cdot 25} = 960 \text{ ohms.}$$

Now use the formula for parallel working.

$$\frac{1}{R_T} = \frac{1}{1920} + \frac{1}{960}$$

Here R_T means the total resistance

$$\frac{1}{R_T} = \frac{3}{1920}$$

Now turn this upside down:

$$R_T = \frac{1920}{3} = 640 \text{ ohms.}$$

Now apply Ohm's Law to find the current and we have

$$I = \frac{240}{640} = \frac{3}{8} \text{ ampere.}$$

The two ways of doing this problem are given because each throws light on the other.

Finding the two currents and adding these together is the simple way, but when the formula is used, that is what we are really doing, but we are keeping it in the background.

$\frac{1}{R_1}$ tells the current in the first lamp for 1 volt.

$\frac{1}{R_2}$ tells the other current for 1 volt. The formula

$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$ is therefore obvious for it merely says the two currents can be added together.

Here is another problem which will yield to careful thought if you have understood what has been said about Ohm's Law. Can you do it? A twelve-volt battery is connected to three resistances as shown. Find the current in each resistance. (See Fig 13).

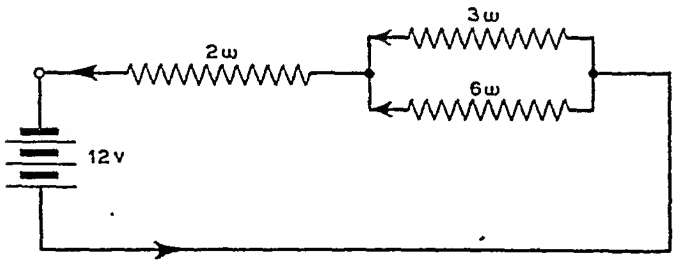


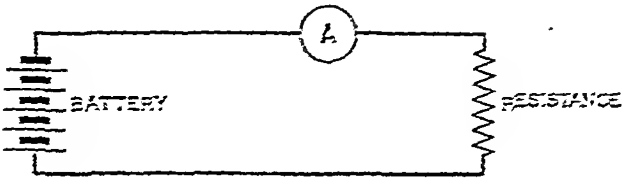
FIG. 13.—BATTERY WITH RESISTANCES IN SERIES AND IN PARALLEL.

It is very useful, also, to be able to understand voltmeters and ammeters and make them measure smaller or larger currents at will. The following calculations will help you to do this.

CHAPTER IV

CALCULATIONS ON VOLTMETERS AND AMMETERS

WHEN an instrument is used to measure the current flowing in a circuit it must be included in the circuit as shown in Fig. 14.



For instance, suppose the meter alone indicated 1 scale division for ·001 amp.

Now if it had an external resistance leak of 1000 ohms, it would read 1 volt per scale division because 1 volt sends 1 milliamp. through 1000 ohms by Ohm's Law. This neglects the actual resistance of the meter.

Generally the coil of the meter has some resistance and this must be subtracted from the 1000 to give the actual leak value, so that both together form the thousand or whatever is wanted.

Example 5. A meter with a 100-ohm coil moves four scale divisions for 1 milliamp. Find the external resistance which must be used to make the meter read 2 volts per division.

Four divisions per milliamp. means
One division ,, ·25 milliamp.

As we want 2 volts per division, it follows that 2 volts must cause ·25 milliamp. to flow.

$$R = \frac{E}{I} = \frac{2}{\cdot 00025} = 8000 \text{ ohms.}$$

The coil of the instrument has 100 ohms so the external resistance must be $8000 - 100 = 7900$ ohms.

Ammeters.

With an ammeter on the other hand, it is usual to place a

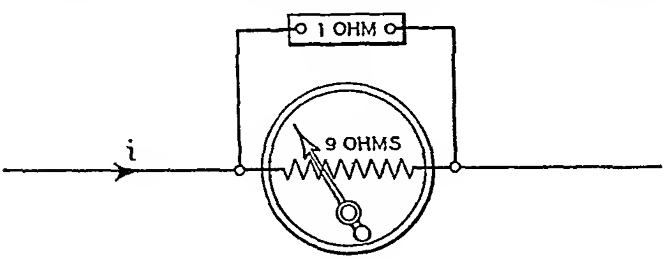


FIG. 16.—AMMETER SHUNTED WITH LOW RESISTANCE.

low resistance shunt across the coil so that only a small fraction of the current flows through the meter.

Suppose the meter has 9 ohms resistance and it is shunted by 1 ohm thus. (See Fig. 16).

The current in the shunt will be nine times as great as the current in the meter. Thus one-tenth of the total current will flow through the meter.

Example 6. A meter with a 500ω coil reads up to 6 milliamps. full scale, and it is required to make it read 6 amps. full scale; find how big the external shunt should be.

A current of 6 amps. is a thousand times larger than one of 6 milliamps., therefore the total current in the meter and shunt must be a thousand times the current in the meter alone. This means the shunt current must be 999 times the meter current, i.e. the shunt resistance must be $\frac{1}{999}$ of the meter resistance.

Shunt resistance then $= \frac{500}{999} = \cdot 5005$ ohms.

This follows from the fact that the actual working of the instrument itself is unaffected by any external apparatus, i.e. let 1 milliamp. flow through its coil and it will always have the same deflection whatever shunts may be in use.

Measurement of Resistance.

A good method of measuring a resistance is to apply a battery to the resistance and measure the resulting pressure E and the current I. The circuit for doing this is shown in Fig. 15.

The value of R is given by $R = \frac{E}{I}$

The ammeter should have very low resistance so that there is no loss of pressure or fall in voltage in drawing the current through it. The voltmeter should have very high resistance in order not to pass a current which may be more than is carried by the resistance under test. Most instruments are not accurate, nor are they made so that these two important points are allowed for. A better way of measuring is to use a method invented by Sir Charles Wheatstone.

Wheatstone's Bridge.

When the first Atlantic Cable was laid, considerable trouble was experienced. Faults developed, and it became necessary to raise the faulty portion of the cable to the surface for repairs. It will be realised that the task of raising the whole cable borders on the impossible, and it became necessary to have a convenient method of locating faults.

A resistance measurement is generally sufficient, for the cable makers know the resistance per mile of the cable and the sea conducts electricity very well, so that the problem reduces to a division sum.

Let the resistance of the cable be 2 ohms per mile, and let the measured resistance from the end to the fault be 2000 ohms. (See Fig. 17).

But where did the fault lay? It might be anywhere between England and America.

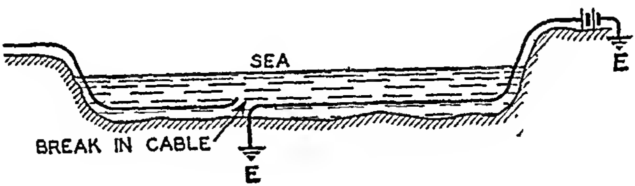


FIG. 17.—A SUBMARINE CABLE WITH A FAULT.

The distance of the fault from the end at which the measurement is made will be

$$\frac{2000}{2} = 1000 \text{ miles.}$$

The Wheatstone Bridge consists of: (i) Three Resistances; (ii) Two Keys; (iii) A Galvanometer; (iv) A Battery.

These are arranged as in Fig. 18.

The beauty of this circuit is that the measurement does not depend on the accuracy of the galvanometer which should, however, be sensitive. The three resistances "*a*," "*b*" and "*R*" must be accurately known and must be adjustable. Measurement is made by adjusting "*R*" and if necessary "*a*" and "*b*" too, until the galvanometer reads zero. When it does so, there is a simple relation by which

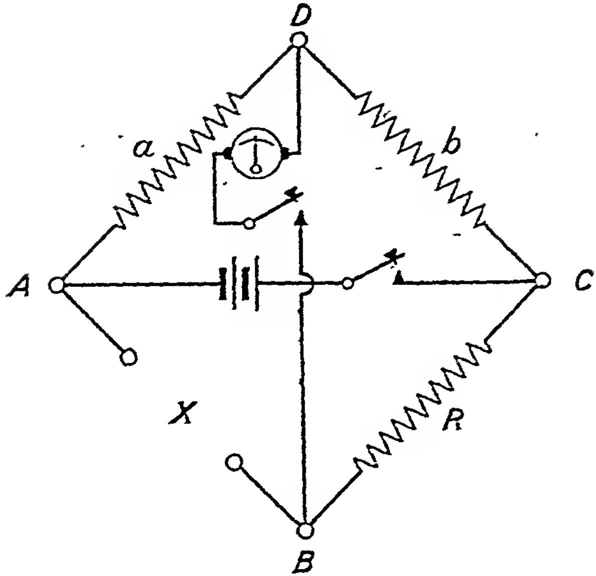


FIG. 18.—THE WHEATSTONE BRIDGE.

When balanced by varying R until the Galvanometer remains stationary, the value of any unknown resistance is found from the relation $a : b :: x : R$.

the unknown resistance X may be calculated from the known values "a," "b" and "R."

This relation is $X = \dfrac{aR}{b}$.

The proof of this is as follows. The full battery voltage V is applied between A and C. This pressure is used in sending a current i_1 along ADC and in sending a current i_2 along ABC.

By Ohm's Law the pressure between A and D, i.e. the pressure across resistance "a" will be i_1a.

Similarly the pressure across X will be i_2X.

If the pressure drop along "a" is equal to the pressure drop along X, the points D and B will be at the same pressure

or "potential" and there will be no tendency for any current to flow through the galvanometer in either direction.

It is necessary, then, when the bridge is "balanced" to make G read zero,

$$ai_1 = Xi_2$$

Further, if the pressure across "X" is equal to that across "a," the remainder of the battery pressure across "b" will be equal to that across R.

Therefore we have:

$$bi_1 = Ri_2$$

Now take these equations and divide the first by the last. This gives, in accordance with the rules of algebra

$$\frac{ai_1}{bi_1} = \frac{xi_2}{Ri_2}$$

The i_1 and i_2 cancel leaving

$$\frac{a}{b} = \frac{x}{R}$$

Multiplying both sides by R gives

$$x = \frac{a}{b}R.$$

Example 7. In a Wheatstone Bridge test the ratio arms are 100ω and 1000ω respectively. R = 143 for balance. Find the resistance of the apparatus under test.

$$x = 143 \times \frac{100}{1000} = 14{\cdot}3 \text{ ohms.}$$

Construction of Bridges.

There are two main types of variable resistance for use in bridges, one is the dial type and the other the plug type.

Dial Type Resistance.

In the variable resistance arm, "R" of the bridge, may be four dials: thousands, hundreds, tens and 1

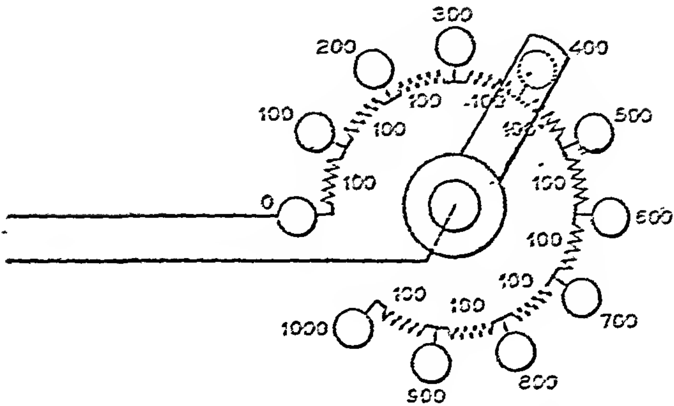


FIG. 19.—A DIAL TYPE OF VARIABLE RESISTANCE.

The sketch shows the "hundreds" dial consisting of ten equal resistances of a hundred ohms each. (See Fig. 19).

Plug Type Resistance.

This resistance consists of a heavy brass or copper bar slotted at intervals as in Fig. 20.

When the plug is inserted, the particular coil is short circuited, but when the plug is withdrawn, current has to

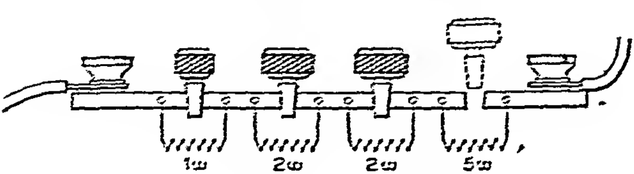


FIG. 20.—PLUG TYPE VARIABLE RESISTANCE.

flow through the coil, which is therefore in circuit. For convenience, the two ratio arms *a* and *b* together with the variable resistance *R*, are usually made up in one instrument as shown in Fig. 21.

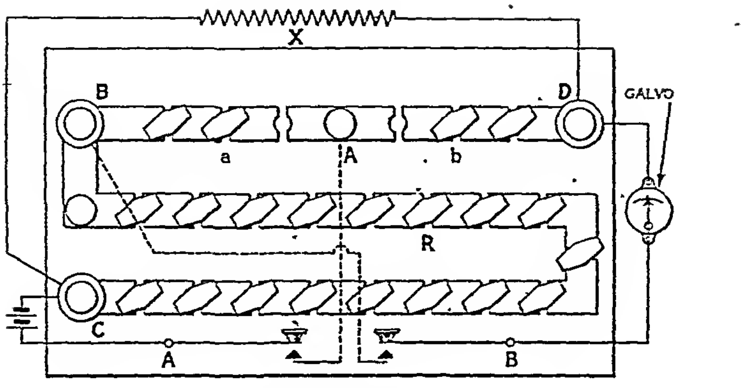


FIG. 21.—BOX PATTERN WHEATSTONE BRIDGE.
Commonly called the Post Office Box.

Fig. 21 shows the layout of this box pattern Wheatstone Bridge. The main brass sections are divided into segments and accurate resistance spools are wound and terminated on them, connection being made by soldered joints. The diagram shows the circuit clearly. The coils, which are wound in a special manner are either short-circuited or brought into circuit by manipulating the brass plugs.

The dial type of resistance is much better as it is far less trouble to use, and there is no virtue in making anything difficult to use.

CHAPTER V

MORE ABOUT RESISTANCE

Calculations on the Resistances of Conductors.

HITHERTO we have solved problems involving resistances, but have given no account of the method of determining how the resistance of any conductor may be found. The resistance of a conductor depends on two things, first on the nature of the material of which it is made, and secondly on its form, or shape.

If we take then a certain shape as standard we shall have a standard or *Specific Resistance* for every material. The usual standard is either a centimetre or an inch cube. The specific resistance is the resistance between two opposite faces of the cube.

Measured in this way, a cube of copper 1 cm. each way has a resistance of $1 \cdot 594 \times 10^{-6}$ ohms. The following table gives the results of similar measurements on other materials. The resulting value is usually denoted by the Greek letter ρ. (Pronounced roe.)

It will be seen that silver is the best conductor. Since it is fairly cheap, electric wires are, for most purposes, made of copper. Where the weight, but not the bulk, of the material is important, as in overhead conductors, aluminium is frequently used. The cable may consist of several strands of aluminium twisted round a core of stranded steel, the latter giving strength to withstand wind, snow, etc.

Such a conductor is manufactured by the British Insulated Cable Co., at Prescot, for overhead use in England, in connection with the "Grid Scheme" of electric power distribution.

The problem of the electrical engineer is to determine the resistance of a wire or other conductor when the dimensions and specific resistance are given.

First consider two cubes end to end, as in Fig. 22.

The measurement between A and B will be the measurement of two resistances in *series* which is 2ρ. Similarly with 3 in series it will be 3ρ. Consequently a rod l inches long will be $l\rho$ ohms resistance if its cross section is 1 sq. cm.

What is the effect of altering the cross sectional area? If two rods of length "l" cms. are placed in parallel, the resistance will be halved, i.e. $\frac{1}{2}\rho l$. Consequently the resistance of a wire is therefore smaller, the larger the cross sectional area, and we have as the complete formula:

TABLE OF SPECIFIC RESISTANCES.

MATERIAL.	Ohms per 1 in. cube.	Ohms per 1 cm. cube.
Silver	$\cdot 56 \times 10^{-6}$	$1\cdot 5 \times 10^{-6}$
Copper	$\cdot 626$	$1\cdot 59$
Aluminium . . .	$1\cdot 065$	$2\cdot 705$
Iron	$4\cdot 16$	$10\cdot 57$
Cast Steel	$7\cdot 87$	20
Cast Iron	$39\cdot 35$	100
Eureka (60 % Copper) (40 % Nickel) . .	$19\cdot 29$	49
German Silver . . . . (4 % Copper) (2 % Nickel) (1 % Zinc)	$8\cdot 68$	22

$$R = \rho\,\frac{l}{a}$$

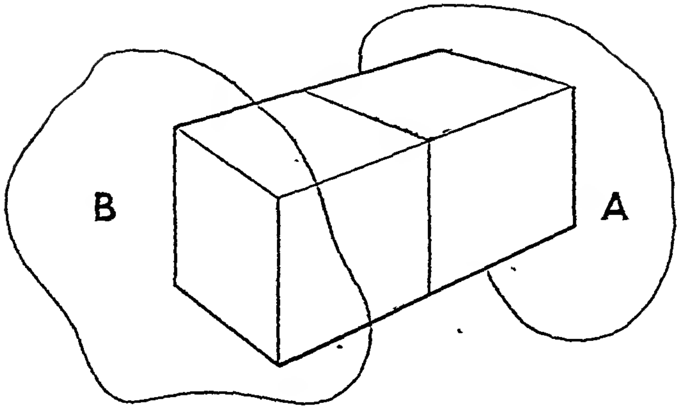


FIG. 22.—CONDUCTOR MADE OF TWO CUBES IN SERIES.

This is summed up by saying that the resistance of a conductor is directly proportional to its length and inversely proportional to its cross section. The actual form of the cross section has nothing to do with the matter; it is immaterial whether the shape be round, square, oval, or any other outline.

Example 8. Find the resistance of 1 mile of wire $\frac{1}{4}$ inch in diameter, as used for the overhead conductors on tramway systems.

First find ρ per inch cube. The table of specific resistances tells us that it is ·626 microhms from table.

The AREA of a wire $\frac{1}{4}$ in. diam. is

$$\frac{\pi}{4}\left(\frac{1}{4}\right)^2 = \cdot 049 \text{ sq. in.}$$

There are 1760 yards in a mile, so

$$l = 1760 \times 36 \text{ ins.}$$
$$a = \cdot 049 \text{ sq. ins.}$$
$$\rho = \cdot 626 \times 10^{-6} \text{ ohms.}$$
$$R = \frac{\cdot 026 \times 1760 \times 36}{10^6 \times \cdot 049} = \cdot 809$$
$$= \cdot 809 \text{ ohms.}$$

If therefore a tramcar takes 50 amperes there will be a loss of 40·45 volts if the car is a mile away from the substation.

Internal Resistance.

It has been found that every battery offers some resistance to the passage of an electric current, although it may be generating that current. This is called internal resistance to distinguish it from the resistance of the external circuit.

When the battery is giving out a current, power is wasted in overcoming this internal resistance for some proportion of the battery's electro motive force is used up in driving the current through the battery itself. This means that the battery voltage will be rather less, when a current is being taken, than when the battery is on open circuit.

Example 9. Take a simple example:—A battery with an open circuit e.m.f. of 2 volts has an internal resistance of 1 ohm. (See Fig. 23.) What is the voltage given by the battery, the current flowing, and the power wasted in the internal resistance, when the battery is connected to an external resistance of 4 ohms?

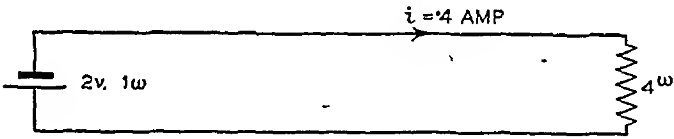


FIG 23—FINDING THE INTERNAL RESISTANCE IN THE BATTERY.

Adding together the resistances 4 and 1 we have

$$I = \frac{2}{5} = \cdot 4 \text{ ampere.}$$

This is the current flowing through the battery, and through the external resistance. The voltage of the battery is divided into two parts, one part to send the current through the internal resistance and the remainder to send the current through the external resistance.

The voltage across the external 4ω resistance is $4 \times \cdot 4 = 1 \cdot 6$ volts.

The voltage used in the cell is 2 — 1·6 = ·4 volts.

The power used externally is 1·6 × ·4 = ·64 watts and that used internally is ·4 × ·4 = ·16.

If now we define the efficiency of the cell as $\dfrac{\text{power out}}{\text{total power}}$ the efficiency in this case is ·64 = ·8 or 80 per cent.

The power going out from a cell is dependent on the external resistance as well as on the internal resistance and the open circuit voltage. If the cell be short circuited no power is used outside, though power is wasted within. Nor is any power used either outside or inside when the cell is open circuited.

Is it possible to find a resistance which shall draw the maximum power out of the cell? The only thing to do is to plot a graph of power against External Resistance.

Putting in tabular form we have:

R	*I*	*W*
½	1·33	·888
1	1·00	1·00
1½	·800	.960
2	·667	·888
3	·500	·750

This gives a graph of the form shown below in Fig. 24.

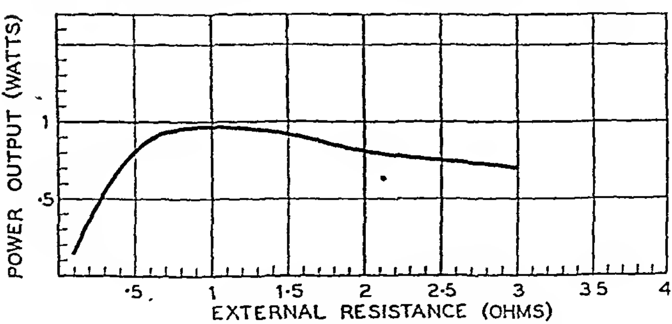


FIG. 24.—THE POWER DELIVERED BY A BATTERY.

It is important to note that the maximum power output is obtained when the External Resistance is made equal to the Internal Resistance of the battery. This comes into the theory of the design of transformers for wireless sets and the thermionic repeaters (amplifiers) which are now being used on long distance telephone lines.

More Problems on Ohm's Law.

(1) *One lamp takes 8·2 amps at 7·1 volts and another 6·9 amps. at 8 volts. Which is the more powerful?*

(2) *A train operating on a 600-volt line, takes 2000 amperes. Find the horse power. (One H.P. = 746 watts).*

(3) *A tram working on a 600-volt circuit takes 100 amps. Find the horse power.*

(4) *A 60 watt lamp works on a 400-volt circuit. Find its resistance.*

(5) *Find the current required by a 400-volt crane motor to raise a load of 1000 lbs. at 100 feet per minute.*

(6) *Current is supplied over a cable of ½ an ohm resistance to light a town which takes 20 amps. The dynamo voltage is 400. Find the horse power required to drive the dynamo, the resistance of the lamps and the voltage lost on the cable.*

(7) *Draw a diagram of a Wheatstone Bridge (P.O. type) showing the connections.*

(8) *A 2-volt cell has an internal resistance of 1 ohm. Draw a graph showing the relation between the value in ohms of a resistance connected to the battery, and the power wasted in this resistance.*

(9) *An ammeter with a 500ω coil reads up to 6 milliamps. Find the resistance of a shunt to make it read up to 6 amps.*

(10) *A cell with an e.m.f. of 4 volts has an internal resistance of ·1 ohm.*

An external resistance is connected to it.

Draw a graph showing the efficiency of the circuit for various values of this resistance.

The student is advised to make up problems for himself. That is the royal road to a good understanding.

CHAPTER VI

ELECTRO-MAGNETIC INDUCTION.

IT was a great moment in the history of science when Hans Christian Oërsted, of Denmark, discovered that a wire carrying an electric current could deflect a magnetic needle. A simple discovery, and yet it meant that a connection between electricity and magnetism had been found. An electric current produces a magnetic flux and this is a link between the "electrical" world and the "magnetic" world. To-day we have to deal with a second "link" which is more remarkable than the first.

WHENEVER A MAGNETIC FLUX *CHANGES*, IT GENERATES AN ELECTRIC VOLTAGE IN PATHS SURROUNDING THE FLUX.

The simplest way of proving this is to take a coil and connect it to a galvanometer then thrust a bar magnet into the coil, as in Fig. 25.

As the magnet is introduced into the coil, the galvanometer needle indicates that a current is being generated in the coil.

(1) When the magnet is stationary there is no deflection.

(2) When the magnet is pulled out, the deflection is in the opposite direction to when it is being pushed in.

(3) To push in the "South" pole produces an opposite deflection to that produced by pushing in a North pole.

The flux in this experiment is provided by the bar magnet but it is unnecessary to use a permanent magnet. A separate coil of wire and a battery will do. In this case two coils are taken so situated that when a current is sent round the primary coil *P*, the flux produced cuts through the secondary coil *S*. The galvanometer needle will flicker whenever the key is opened or closed, but will come to rest when the key is left at rest in either position.

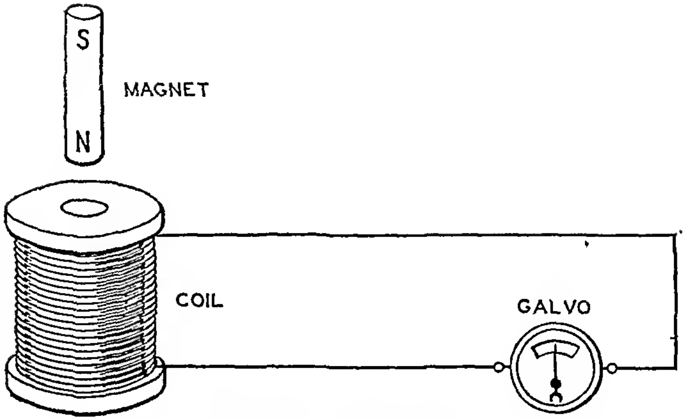


FIG 25.—E M F. INDUCED IN A COIL BY A MAGNET.

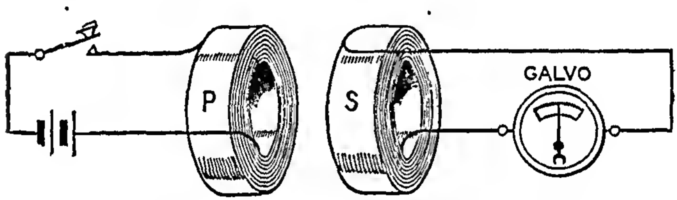


FIG. 26.—CURRENT INDUCED BY ONE COIL IN ANOTHER.

Summary.

What has gone before in these few pages sums up a great deal of labour and research on the part of many people.

Electricity is in small, very small bits or *electrons*. When these move we have *electric current*.

A battery or dynamo is a kind of pump to cause a flow of current.

Current we measure in Amperes, but the pressure causing the current we call Voltage, measured in Volts.

Current flows in a circuit though electrons may crowd together somewhat if their flow is caused by a break in the path. Metals conduct the current well. We say they have a "low resistance". Resistance is measured in Ohms. When we know the voltage of the battery or dynamo and the

resistance of the circuit, it is easy to calculate the current. It is a simple division sum.

This rule, called Ohm's Law is exceedingly important. Few substances disobey it. Use it on every part of a circuit and on the whole circuit. One then gets useful rules like adding resistances in series and the other rule for resistances in parallel.

Power is measured in watts, being voltage times current in amperes. The next thing of importance is that a current in a wire or anywhere causes a magnetic flux. If the flux flows in air—the flux is proportional to the current.

Last of all comes Faraday's electro-magnetic induction.

A *changing* magnetic flux in any loop or coil of wire causes a voltage to be induced in the loop or coil. This is the principle of the dynamo and transformer.

The condenser is a study in itself. It consists of conductors separated by an insulator. Electron currents flow to and from the plates during charge and discharge. An ether displacement current flows in the insulation too. This has power to cause magnetic effects no less than current in a wire, the ordinary electron current.

In a circuit containing a condenser for example the electron current in the conductors and the "Maxwell" current in the insulator form a circuit so current *always* flows in circuits. This is a key to radio work.

Faraday discovered electro-magnetic induction, which is the principle of the modern transformer, and also made momentous experiments on charged bodies, which led to the invention of "condensers" as we now call them. These are metal sheets interleaved with an insulator. The two plates or sets of plates may be charged like a battery, but hold a very small amount of electricity. Faraday's magnetic and electric experiments are the foundation of modern circuit theory.

Alternating Current.

There is one way in which the secondary may light a lamp continuously and that is to feed an alternating current into the primary winding. An alternating current is one which reverses its direction in the circuit periodically. Thus the alternating current from the Liverpool Corporation Supply

starts from zero, grows to a maximum, falls gently to zero, changes direction, gains strength and then falls to zero, to repeat this complete cycle again every fiftieth of a second.

A time graph of an alternating current is shown in the following figure:

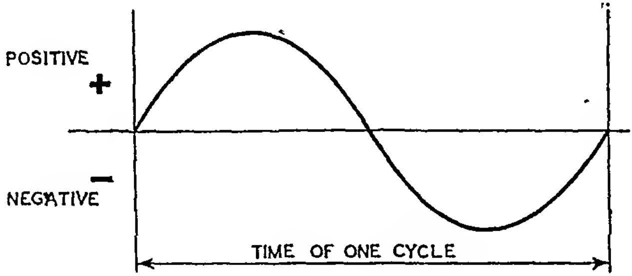


FIG. 27.—CURVE OF AN ALTERNATING CURRENT.

Under these circumstances, the flux in a transformer will be varying from moment to moment and an alternating pressure will be generated in the secondary coil, causing a current to flow therein, so that a lamp may be lighted if connected.

It should be noticed that it is the flux change that matters and for purposes of calculation it is well to remember that a change of flux of 100,000,000 lines per second produces a volt in every turn of wire through which the changing flux passes.

It is this dual connection between electricity and magnetism which makes the phenomena so interesting.

Why a current produces a flux or why a changing flux produces a voltage we do not know. This is the real wonder at the back of all electrical invention, and it is well to remember that if it were not so, no amount of research work or human skill would be of any avail. The outstanding wonder of the world we live in, is not that inventions have been made, but that the universe has these fundamental properties which we do not know anything about, but which make us able to build our transformers, our telephones and wireless sets, and then see them work.

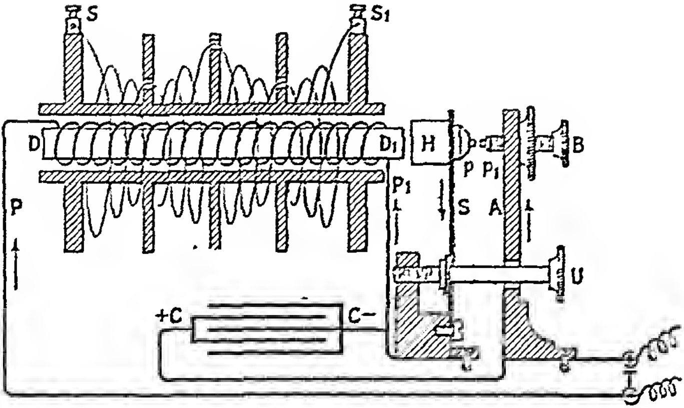


FIG. 28.—THE CONSTRUCTION OF AN INDUCTION COIL.

The Induction Coil.

In order to obtain high voltages for experimental work, the principle of electro-magnetic induction is used in the construction of special "Induction Coils". Such a coil is constructed as follows:

There is a primary winding surrounding a core of soft iron wires, and outside this a secondary winding consisting of a large number of turns.

The primary winding is connected through an interrupter to a battery thus producing an intermittent flux in the core. The changing flux in turn produces the voltage in the secondary coil. The changing flux induces a voltage in each turn of the secondary, and therefore the larger the number of secondary turns, the greater the total induced voltage.

Any form of contact breaker will do, and the most convenient is the electric bell type shown in the sectional drawing (Fig. 28).

The sequence of operations is as follows:

The battery sends a current round the primary, magnetising the iron wires in the core.

This current flows through the contacts P, P_1 which are short circuiting the condenser. This therefore plays no part as yet.

The current in the coil at first rises rapidly and then more slowly until the contact breaker is opened by the increasing magnetic flux in the core.

Why does the current take time to rise? Why do we not have $I = \frac{E}{R}$ the moment the battery is connected? The reason is that the rising flux generates a voltage in the primary as well as in the secondary. This induced primary E.M.F. opposes the battery, and therefore limits the rate of rise of flux.

As a matter of fact the flux rises so slowly, that the induced secondary voltage is at this stage insufficient to perform experiments.

As already stated, the flux rises until the magnetic pull opens the contact breaker. The moment the contact points separate, the current in the primary winding is diverted into the condenser. As the condenser becomes charged, the charge current falls in volume. The falling current can only produce a falling flux. This induces the working pressure in the secondary.

There is a pressure induced in the primary coil, and this helps to send a bigger current into the condenser, which therefore charges it up to a higher voltage.

When the primary current has died down to zero the condenser is fully charged and has a high pressure on its terminals.

It therefore now sends a reverse current round the primary coil, and this wipes out the last traces of magnetism in the core. It may be asked why a condenser is used at all? Would not the break in the current be more sudden if the condenser were omitted? Curiously enough, the answer to this question is "No". If an attempt be made to stop the current suddenly by opening the contact breaker, without a condenser, the voltage induced in the primary winding alone is sufficient to strike an arc across the points, and as this arc takes some time to die out, the decay is actually slower than when a condenser is used.

The only other point calling for mention is the use of iron wires for the core. The reason for this is that a flux can decay much more quickly in a core of iron wires than in a

solid core, a phenomenon which is due to the production of eddy currents in the iron itself.

Suppose the following diagram to represent the cross section of a solid circular iron core, carrying a changing flux.

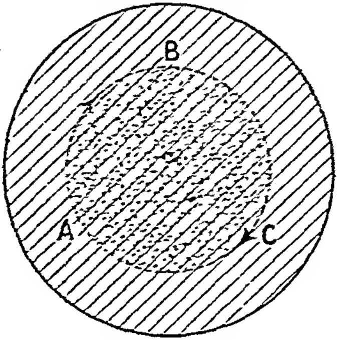


FIG. 29.—EDDY CURRENTS.

Consider any circle such as ABC. The changing flux within generates a voltage in the circle, for the circle certainly surrounds the space lying inside it. The circle is a path in the iron, and iron conducts electric currents as well as magnetic fluxes.

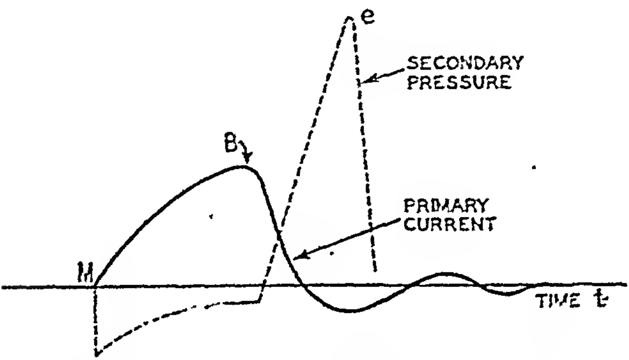
All these "eddy" currents oppose the flux change, and therefore lessen the efficiency of the coil. To break the core up into a number of parts all electrically insulated from each other, decreases this effect.

It is for the same reason that the cores of alternating current transformers are made of sheet metal and the core of the induction coil in a subscriber's telephone set is made of iron wires.

As a matter of interest it may be stated that every telephone relay waits, after the current is switched off, before commencing to release, due to the presence of eddy currents in the core. A relay with a copper slug will have heavy eddy currents induced in the slug while the flux is decaying and, for this reason, such a relay is slow to release. The impulse (A) relay in the Auto Telephone System when entirely disconnected

from battery will wait for 7 milliseconds due to eddy currents in the iron, while the "*B*" relay fitted with a copper slug $1\frac{1}{2}$ in. long will take perhaps 300 milliseconds to release.

It will be well to graph the primary current, and the secondary voltage in a working induction coil.



M SIGNIFIES THE MOMENT OF "MAKE" OF THE CONTACTS
B " " " " "BREAK" " " "

FIG. 30.—CURRENT AND VOLTAGE IN AN INDUCTION COIL.

Transient Currents.

The induction coil offers an excellent opportunity to study transient currents. One of the simplest transients is the rise of current in the primary when the contact breaker closes. A flux proportional to the current, rises as the current rises. This rising flux generates a back e.m.f. in the coil proportional not to the flux but proportional to its rate of increase. Some of the battery voltage is spent in overcoming this back e.m.f., the rest in driving the current of size I at that moment say, through the coil resistance R according to Ohm's Law $E = RI$. When I is small so is RI and there is plenty of voltage left to overcome back e.m.f. so the rate of flux and current rise is rapid at first.

The induction coil is a fine illustration of the principles of induced voltage and current.

CHAPTER VII

EXPERIMENTS ON "SPACE"

THE induction coil can, then, be used to produce surges or impulses at high voltage. The coil used in the following experiments developed about 30,000 volts. This pressure lasts however for such a very short time that little energy is given out. If the terminals of the coil are examined in a dark room it will be found that they glow with a faint bluish light. This effect is due to a discharge of electricity into the air.

When two wires connected to the terminals are brought near to each other, a stream of sparks passes between the wires, one spark at each interruption of the primary current. The sparks indicate that the air in the space is being broken down. In the same way, the spark will penetrate a piece of cardboard, leaving a hole. When the wires are separated too far for a spark to pass, it is natural to ask whether the working of the coil can have any influence on the space surrounding the wires. This can only be settled by experiment.

Connect the coil to two plates placed parallel to each other and say two feet apart. When the coil is working, the plates are charged at each "break" and discharged in between the "breaks".

Can a lamp be lighted in the space between the plates?

A neon lamp such as is used for a "night light" will, if fitted with small plates, as shown, actually glow when placed in the space between the plates. It is difficult to over-emphasise the importance of this experiment, for though a wire carrying a current is surrounded by a magnetic field, this lamp does not glow by magnetism. It glows because something has happened to the space in between the charged plates. Exactly what has happened, we do not know.

Prof. James Clerk Maxwell, a brilliant Scotch mathematician, the first Director of the Cavendish Laboratory at Cambridge University, whose life and work made a great impression on all who came to know him, suggested that there was a dis-

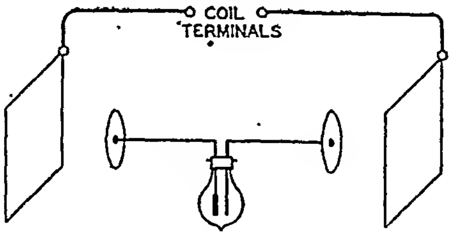


FIG. 31.—LAMP LIGHTED BY SPACE CURRENTS.

placement of "ether" between the plates when charged. When we charge a condenser we believe electrons to crowd on to one plate and drain away from the other. One would say that the electric charge and discharge currents finished at the plates, but Maxwell saw that though the flow of electrons stopped at the surfaces of the plates, there was what he called a displacement of ether between them. Is a displacement of ether entitled them to be called an electric current? The great test for an electric current is whether or not, there is an accompanying magnetic field.

The ether displacement does produce a magnetic field and here we have the mechanism of a wireless wave revealed.

Maxwell foretold wireless waves long before anyone knew how to produce them, and though few people could grasp the meaning of his work, some attempting ridicule—he still continued writing with an air of quiet confidence. He suggested that ordinary light was a wave in the "ether" and gave the equations for determining its velocity of travel. He went on to show that any other ether wave would travel at the same high speed, viz., 186,000 miles per second.

Once admit that the ether can be "displaced" whatever that may mean, and that this displacement really is an electric current, then it becomes possible to see how a wireless wave travels. The displacement "current" must like all currents,

produce a magnetic force. If the ether can carry a magnetic flux, such a flux must be produced by this magnetic force.

As the wave moves, this flux measured at any place, will change and we know that changing magnetic fluxes produce voltages. The voltage in turn "charges" or displaces the ether and now we are back to where we started. There is a four-linked chain. As the chain is complete the wave is self supporting, which proves the possibility of the existence of such a wave.

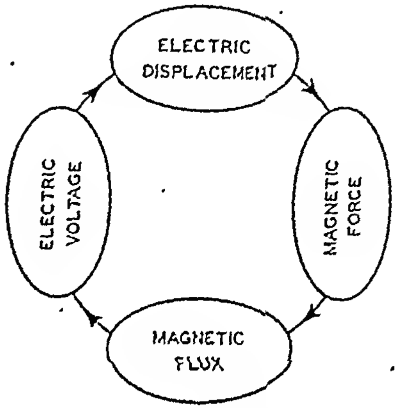


FIG. 32.—THE ENDLESS CHAIN ON WHICH A RADIO WAVE MOVES.

But what is the ether? Once again we do not know. We believe it stretches throughout all space. It must stretch out beyond the earth's atmosphere to the furthest star in order to carry the waves of light to our eyes.

If we stand on the shore we see waves coming towards us. The waves would not be there but for the water. If we stand by a field of ripening corn in late summer and watch the breezes make the corn sway backwards and forwards, we say that the corn is waving in the breeze.

Once again, there could be no wave without the corn, and if light is a wave there must be something to do the "waving". This something has been called "ether" for want of a better name. We believe the ether even penetrates substances; for otherwise how could a ray of light pass through glass?

If two plates, separated by an insulator are connected to a battery and the battery then disconnected, the plates will themselves behave like a battery and send a current round a circuit when connected together by a wire. The current soon ceases, however, and though the plates act like an "accumulator" the charge is so small as to be useless for most purposes. Such an arrangement is called a condenser and a

condenser will fill to any fulness depending on the voltage used to charge it.

If q = the quantity of electricity in coulombs in the condenser and C its capacity, the voltage in the terminals while it has the charge q will be given by the equation

$$q = VC \text{ or } V = \frac{c}{q}$$

Capacities are measured in "Farads" named after Faraday, and a 1 farad condenser holding 1 coulomb would be charged to 1 volt. As the farad is a large size of condenser it is customary to use one millionth or a micro-farad as the commercial unit.

A 2 m.f. condenser charged to 6 volts would hold

$$q = VC = 6 \times \frac{2}{1000000}$$

C6 H8

$$= \cdot 000012 \text{ coulombs.}$$

If a current of $\frac{1}{10}$ ampere were taken from the condenser, the charge would last only $0{\cdot}000012 \div 0{\cdot}1 = {\cdot}00012$ second. or about one ten thousandth of a second.

The capacity of a condenser is greater the closer the plates and it varies according to the material placed between.

Some substances give a larger capacity than others. A condenser may be likened to a spring, for in a spring the *Amount of Displacement* = *Force* × *Flexibility* and in a condenser Quantity = Pressure × Capacity.

The larger the capacity the weaker the equivalent spring. And just as a spring can be strained by too great a force so also may a condenser be broken down by too high a voltage puncturing the insulator.

In practice condensers may be large consisting of many square feet of tinfoil and paper, or may be quite small. Some are variable. These usually consist of metal plates strong enough not to bend, and sliding into a fixed set of plates, the two sets being interleaved but not touching, when all "in," i.e. the position of full capacity.

The variable condenser is much used in radio receivers for "tuning in".

CHAPTER VIII

GENERATION OF CURRENTS

IT has been said that a wire cutting a magnetic field has induced in it a voltage depending on the rate at which the field is cut. This principle is used in constructing dynamos.

Example 10. A loop of wire spins round at 3,000 r.p.m. in a field in which 16,000,000 lines of flux thread the coil when its axis is parallel to the direction of the flux. What will be the average and the maximum voltage induced in the loop?

The following sketch exhibits the essentials. The magnets provide the field and are called field magnets. The revolving wires are usually mounted on a piece of iron called an armature.

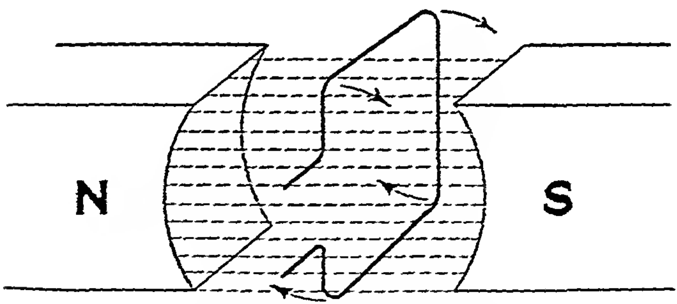


FIG. 33.—SIMPLE DYNAMO.
A Loop of Wire spinning in a Magnetic Field is the fundamental for every Generator.

The loop of wire twists through half a revolution in $\frac{60}{3000 \times 2} = \frac{1}{100}$ second.

During this time each wire cuts right through the flux.

The rate of cutting is then

$$16{,}000{,}000 \div \frac{1}{100}$$
$$= 16 \times 10^8 \text{ lines per second.}$$

We know however that a cutting rate of 10^8 lines per second induces a pressure of 1 volt so we have 16 volts in each wire. There are two wires so the average of the two is twice this. The result is therefore 32 volts.

What is the maximum voltage? It will not be correct to double the average value of 32 because the flux may not grow uniformly from a zero to a maximum. We must find the actual rate of cutting when the coil is in the horizontal plane. We know no dimensions for the circle in which the wire moves. Let it have a radius "r" feet.

We have 3000 r.p.m. or 50 r.p.s. The distance per revolution is $2\pi r$. This makes the actual tangential speed $v = 100\pi r$ feet per second. Incidentally if r is only a foot, v is about 240 miles per hour.

If the radius is r, the diameter is $2r$ and in this space a flux of 16,000,000 lines is contained.

Consequently the lines contained in a foot are $\frac{16 \times 10^6}{2r}$

and with a speed v feet per second the lines cut per second will be $\frac{16 \times 10^6 . v.}{2r}$

As $v = 100\pi r$ this becomes $\frac{16 \times 10^8\pi}{2} = 8 \times 10^8\pi$

Now 10^8 lines per second gives a current with a pressure of 1 volt, so we have 8π volts in each wire, i.e. 16π or 50 volts in the two wires.

It will be of interest to know how the voltage in an armature wire varies from moment to moment. It cannot increase from nothing to a maximum *uniformly* or the maximum (50) would have been double the average which was (32).

Imagine the wire to travel at one foot per second tangential velocity, thus

Velocities can be analysed and compounded as vectors. We can therefore analyse this velocity vector into two, viz., a horizontal, and a vertical one.

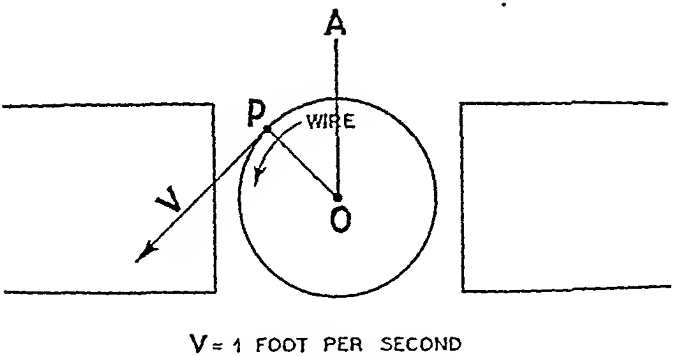


FIG. 34.—THE DIRECTION OF MOTION OF A WIRE ON AN ARMATURE.

If the actual velocity is unity, the Horizontal Component is Cos θ while the Vertical Component is Sin θ.

It is a cutting of the lines which generates the voltage, not a sliding motion. The vertical component Sin θ is therefore all important.

It will be seen that θ, the angle between the actual velocity

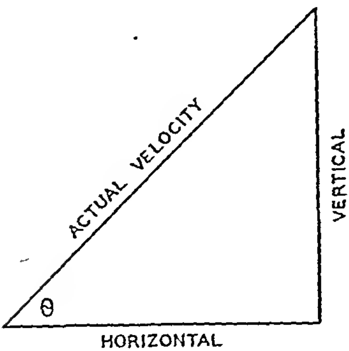


FIG. 35.
RESOLUTION OF VELOCITY INTO TWO COMPONENTS.

vector and the horizontal is the same as the angle *AOP* through which the coil has turned since leaving the vertical position.

The actual voltage developed will of course depend on the density of flux, and for simplicity let it be assumed that we

have 10^8 lines per foot. If then the rate of cutting is 1 foot per second there will be 1 volt generated. In the above example, the rate of cutting is sin θ.

This then is the voltage at any point, i.e. $V = \sin \theta$.

As the shaft moves round steadily, θ grows smoothly, and the growth of V as time passes can thus be predicted from a knowledge of the growth of sin θ. The direction of voltage in the wire will be opposite when the wire is travelling downwards to what will obtain when the wire is travelling upwards.

This is in accordance with what is known of "Sin θ" which is positive when θ lies between 0° and 180° while it is negative when θ lies between 180° and 360°.

As the direction of the induced voltage changes periodically, such voltages and currents are called "alternating".

The shape of the graph $y = \sin x$ is well known and x may be measured in degrees or radians. Often the latter is more useful.

The following graph shows the relation, using radians:

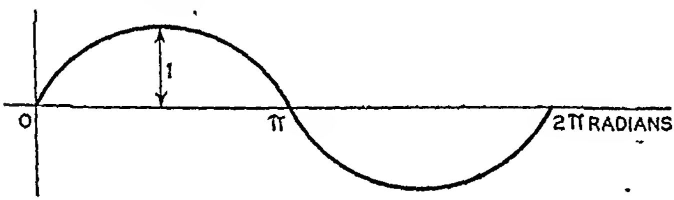


FIG. 36—A SINE WAVE.

The whole time occupied in traversing the cycle, i.e. an angle of 2π is called a "period". "Frequency" is the number of cycles per second. Commercial alternating currents usually have a frequency of 16 to 60 per second. Telephone frequencies range from 400 to 3000 cycles. Wireless waves have a frequency of from 100,000 to 100,000,000 cycles per second.

Since the direct current dynamo and motor are so common their construction and working must be briefly described. We begin with the simplest to understand, namely the "Gramme ring".

CHAPTER IX

DYNAMO CONSTRUCTION

The Gramme Ring Armature.

ONE of the earliest forms of armature was the gramme ring. Imagine a ring wound, in the manner shown in the following sketch, to be placed between the poles of a magnet.

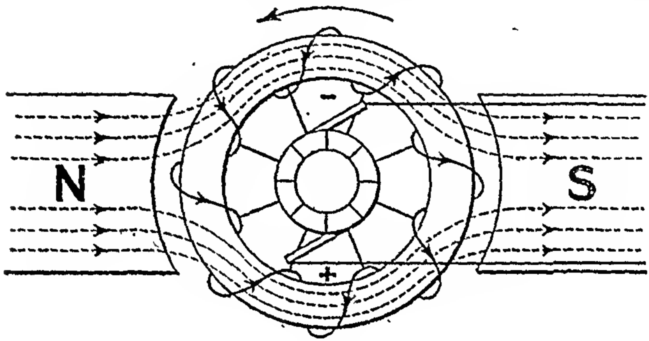
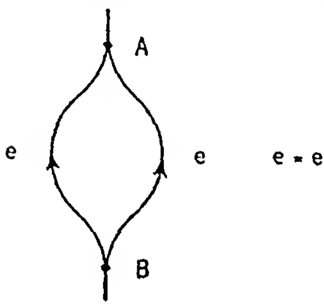


FIG. 37.—THE GRAMME RING ARMATURE.

By applying the right hand rule it will be found that as the ring turns in the direction shown, voltages will be induced in the direction indicated by the arrows. It will be seen that though the armature winding is a closed coil, there is no circulating current for the e.m.f's. induced in one half of the armature balance those induced in the other half—thus:



If now wires be taken from the points A and B, an external current will flow from A back to B. But how to connect an external circuit to a

moving armature? This is done by means of a device known as the commutator which consists of a number of copper bars insulated by strips of mica.

The Commutator.

The copper bars are shaped thus:

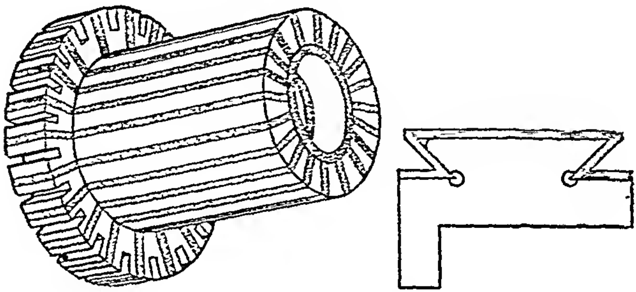


FIG. 38.—A COMMUTATOR.

The commutator bars are connected to the armature coils at intervals, and two brushes, one positive the other negative, press on the commutator at a point midway between the poles to make connection between the armature and the external circuit. It will be seen that as each coil passes under a brush the current in that coil reverses direction. But the current in the external circuit is steady, apart from small fluctuations as each commutator bar passes under a brush.

In this armature, only a small portion of each turn is useful, the inner portion and sides of a turn contributing nothing to the result. The voltage may readily be calculated from the speed, flux and number of turns as follows:

In a two-pole Grámme ring type machine the flux is 500,000 lines in each pole, and there are 16,000 conductors on the armature. Find the voltage generated at 3000 r.p.m.

There are 16,000 conductors on the armature, that is, 8,000 on each side, and each armature cuts the whole flux once per half revolution or every $\frac{1}{100}$ second.

The voltage is then

$$\frac{500{,}000 \div \frac{1}{100} \text{ volts per wire}}{10^8}$$

$= \cdot 5$ Volts.

The whole voltage is then $8000 \times \cdot 5$

$= 4000.$

These figures are approximately correct for an old Gramme ring machine designed for operating arc lamps in series, in the early days of electric lighting. In view of the low efficiency of this machine, a new type of armature known as the *Drum Armature* has been developed. (Fig. 39).

FIG. 39.—A DRUM ARMATURE SHOWING THE SLOTS FOR WIRE.

The Drum Armature.

This has slots for the wires, arranged in the manner shown in the following illustration. (Fig. 40).

The wires are so arranged that this armature is equivalent to the Gramme ring, but the whole turn, with the exception of the ends, is used for generation.

As a typical example of such a winding, take a case in which a two-pole dynamo has 12 slots. The wire is wound backwards and forwards along the slots gradually working round the drum. This can best be accomplished by having a "Forward pitch" and a "Backward pitch". In the case of a twelve-slot armature, let the forward pitch $pf = 7$ and the backward pitch $pb = 5$.

The wire is laid on the 1st slot, brought back along $1 + 7$

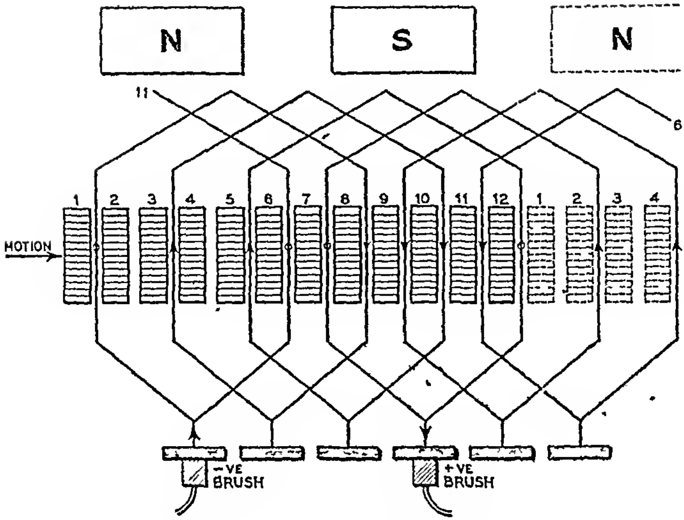


FIG 40.—ARMATURE WINDING OF TWO-POLE DYNAMO WITH TWELVE SLOTS.

= 8th slot, then taken forward along the 8 − 5 = 3rd slot. The slot numbers in order are: 1, 8, 3, 10, 5, 12, 7, 2, 9, 4, 11, 6, then back to slot 1, thus completing the circuit. The following sketch shows the arrangement. It will be noticed that, as on the Gramme ring, the winding forms a closed coil. The

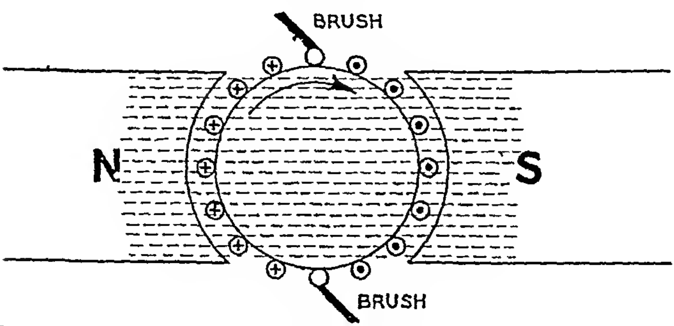


FIG. 41.—BRUSH TAKING OFF THE CURRENT FROM OPPOSED COMMUTATOR SEGMENTS.

arrows indicate the direction of the current flow, and it will be noticed that the brushes are placed on commutator segments leading to coils mid-way between the poles. These wires have been marked with circles indicating that no voltage is being generated therein.

It is a curious fact that the brushes themselves are opposite the poles, not between them, but this of course is merely due to the bending over of the armature conductors as they emerge from the slots.

Number of Wires.

It should clearly be understood that there may be any number of wires in one slot in order to generate a higher voltage. The limit is set by commutation problems for here, as in the Gramme ring, the current in a coil reverses during the brief interval taken for a commutator segment to pass

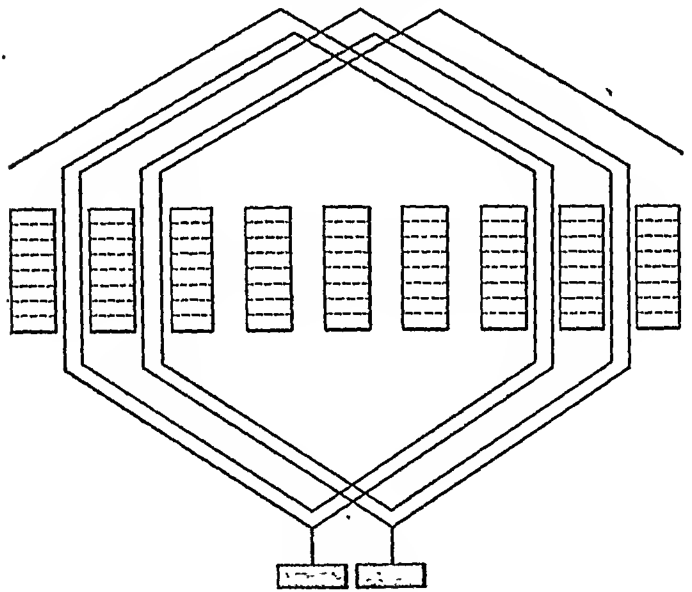


FIG. 42.—ARMATURE WINDING WITH MORE THAN ONE WIRE IN A SLOT.

under a brush. The method of winding with more than one wire in the slot is shown. (Fig. 42).

The Flux Path.

When the armature is in position, the flux passes right through it as shown on the attached sketch of a "Two-Pole Machine". While a two-pole construction is quite common, it is often an advantage to use more than two poles. The poles are then made alternately North and South, the flux

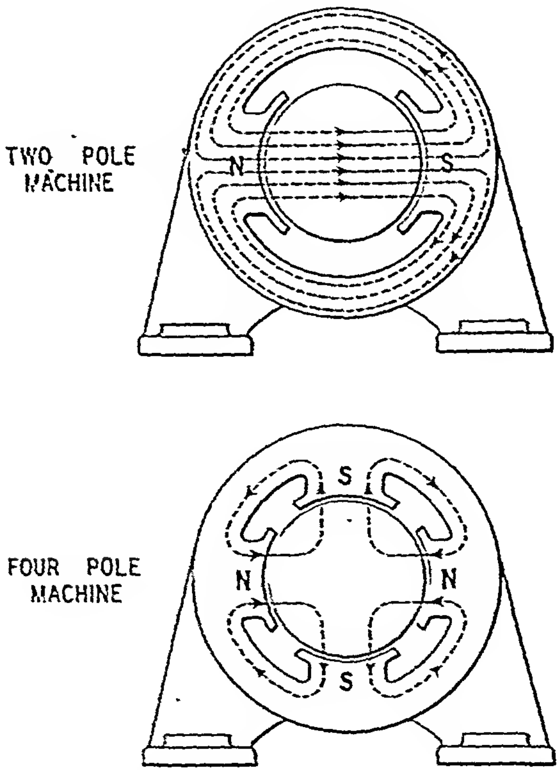


FIG. 43.—THE FLUX PATHS IN TWO AND FOUR-POLE MACHINES.

paths being shown on the sketch entitled "Four-Pole Machine". Such an armature will require a different winding from a two-pole type. If there were 16 slots in all, the pole pitch would be four slots, the forward pitch pf could be 5 and the backward pitch pb could be 3.

The winding would then be: 1, 6, 3, 8, 5, 10, 7, 12, 9, 14, 11, 16, 13, 2, 16, 4 and back to 1. If this winding is laid out as follows, it will be found that there are four parallel paths through the winding, a separate voltage being induced in each path. While the currents in the four paths add together, the voltages do not. As it was necessary to divide the conductors into two, in the two-pole case, here it is necessary to divide by 4.

At the same time, any one armature conductor cuts the flux four times per revolution. Thus it is sufficient in voltage calculations to consider the flux per pole and the total number of armature conductors. This applies merely to the particular arrangement of armature conductors which is known as *Lap Winding*.

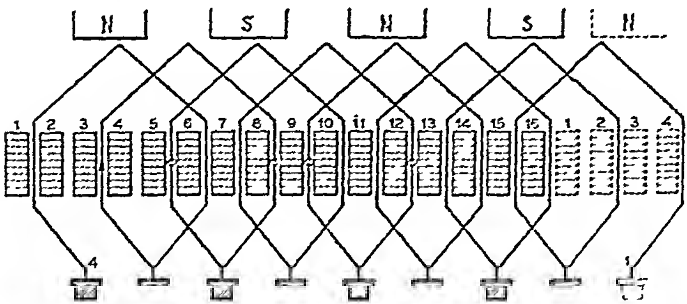


FIG. 44—A FOUR-POLE LAP ARMATURE WINDING.

Voltage.

The output voltage depends on the flux per pole at the time of passing a pole, and the number of armature conductors in series comprising on path through the armature.

The time of passing one pole may be found by dividing the time for one revolution by the number of poles "p".

If the number of r.p.m. is n, the time of a revolution is $\frac{60}{n}$ sec. and the time of cutting through the Φ lines of one pole is $\frac{60}{np}$

Thus the rate of cutting flux is $\frac{np\Phi}{60}$ making the c.m.f. per armature bar $\frac{np\Phi}{10^8 60}$

If there are "a" parallel paths through the armature, the number of conductors joined in series between the brushes will be Z, the total number of conductors on the armature divided by "a". Thus the voltage generated is $\frac{np\,\Phi\,Z}{10^8 a 60}$ where n = r.p.m., p = number of poles, Φ = Flux, Z = Number of Armature Bars, and a = Number of Armature Paths in parallel. In a lap winding $a = p$.

***Example 11.* A 6-pole Lap Wound armature has 400 armature bars, the flux per pole being 5×10^6 lines. What will be the terminal voltage at 1,500 r.p.m.?**

$$
\begin{aligned}
\text{Here } n &= 1500 \\
p &= 6 \\
\Phi &= 5 \times 10^6 \\
Z &= 400 \\
a &= 6
\end{aligned}
$$

$$
l = \frac{1500 \times 6 \times 5 \times 10^6 \times 400}{10^8 \times 6 \times 60}
$$

$$
= 500 \text{ volts.}
$$

There is another common type of winding known as wave winding. Here the two pitches, though unequal, are both in a "forward" direction, and although there may be any number of poles, there are only two parallel paths through the armature.

Excitation.

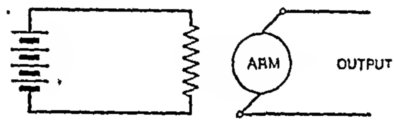
We have not yet stated how the machine derives its current

for supplying the field magnets. There are four systems in use:

(a) Separately excited.
(b) Series Wound.
(c) Shunt Wound.
(d) Compound Wound.

SEPARATE EXCITATION. The field current can be provided by a separate dynamo or battery, thus:

FIG. 45.—SEPARATELY EXCITED MACHINE.



SERIES WOUND MACHINES. Here, the entire armature current passes round the field coils in order to provide the magnetic flux. This arrangement is very seldom used for dynamos but is popular for train motors. The field winding must have low resistance.

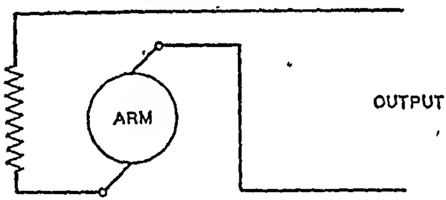
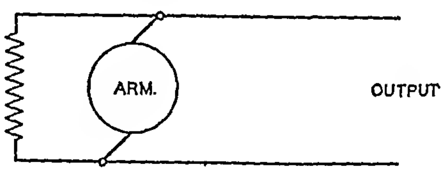


FIG. 46.—SERIES WOUND MACHINE.

SHUNT WOUND MACHINES. Here a portion only of the main current is tapped off to provide the current for the field. The field winding must therefore be of high resistance.

FIG. 47.—SHUNT WOUND MACHINE.



COMPOUND WOUND MACHINES. For reasons which will be given later, it is often desirable to combine both series and shunt excitation.

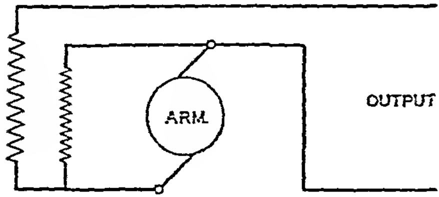


FIG. 48.—COMPOUND WOUND MACHINE.

We have now indicated the underlying principles of the dynamo, but there are numerous points of great importance, attention to which is imperative for the design of a satisfactory machine. For dynamo design, it is necessary to understand the relation between ampere-turns and flux in a magnetic circuit, but before doing this it will be well to outline the distinction between a dynamo and a motor, as a dynamo can be used as a motor and a motor as a dynamo.

The Dynamo.

When the machine is working as a dynamo, the E.M.F. generated by the motion of the armature pushes the current round the external circuit. This current causes a *backward torque* on the shaft which is overcome by the driving engine. *The dynamo is therefore attempting to run in the reverse direction as a motor.*

The Motor.

When the machine is working as a motor, the backward E.M.F. generated by the motion of the armature is overcome by the forward E.M.F. of the current supply. The current which is driven through the armature by the supply E.M.F. against the generated back E.M.F. produces the torque on the shaft. *The motor is therefore attempting to act as a generator in an effort to send a current backwards round the supply circuit.*

The Mechanical Force in Dynamos and Motors.

In a motor or dynamo the conductors carry an electric current and being in a magnetic field they experience a

mechanical force. This mechanical force in a motor is the useful effort which is transmitted through the armature teeth to the shaft. In a dynamo this mechanical force must be overcome by the steam engine in order to turn the armature and generate the voltage. This is necessarily true because the steam engine provides energy of motion. Energy is non-destructible, which principle we call the *Conservation of Energy.*

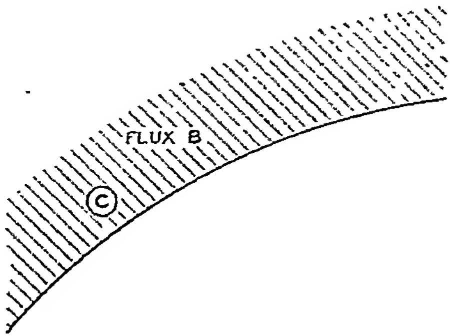


FIG. 49.—CONDUCTOR IN A FLUX.

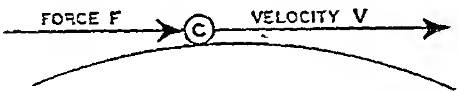


FIG. 50.—MECHANICAL FORCE IN A CONDUCTOR.

For this reason it follows that the mechanical motion energy is equal to the corresponding electrical energy. The relation between the units is that 1 H.P. = 746 watts. The mechanical force will depend on the field strength, on the length of conductor in the field and on the current flowing.

Take an inch of conductor moving in a field of density β lines per square inch. The conductor will have an e.m.f. (E) induced in it which will depend on its length, on the velocity, and on β.

If the induced e.m.f. sends a current i round an external circuit, the *Power* generated will be $E \times i$ watts. It is this power which is equal to the mechanical horse power, equated by the relation 1 H.P. = 746 watts.

The early dynamo makers understood the general principles of induction as expounded by Faraday, but they had very little knowledge of the subject, and their productions were most crude. It was not until Prof. John Hopkinson published an epoch-making paper on the magnetic circuit of the dynamo that a sound theory of design was evolved. This theory we now propose to sketch.

Dynamo Characteristics.

It is known from experiments on electro-magnets that with a small current flowing in a coil surrounding an iron core, the flux is roughly proportional to the current in amperes. At high flux densities, however, the increase in flux becomes less. This effect is known as saturation of the iron.

It is due to the fact that magnetisation of iron is a turning of the molecules so that they tend to lie all in one direction. When all the molecules are so turned, obviously nothing else can be done except that the ether in the spaces between the molecules may take a bigger flux. So far as we know, there is no limit to the flux which can be carried by the ether, so the flux curve never becomes quite flat.

A smaller current with more turns gives exactly the same effect as a large current with correspondingly less turns. It is the product (AMPERES) × (TURNS) which counts. The usual symbol for ampere turns is $\widetilde{A}$. The following curve represents the effect of saturation:

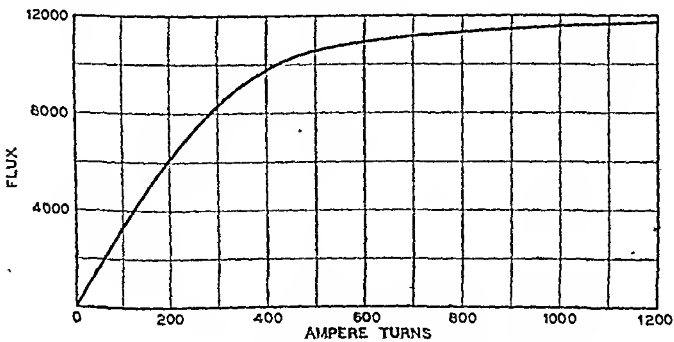


FIG. 51.—FLUX CURVE IN TELEPHONE RELAY.

This curve is drawn for a telephone relay with its armature in the operated position. It has a magnetic circuit just like a dynamo. Our interest, at the moment, in magnetic flux, is its ability to generate e.m.fs. and we are therefore interested in the current flowing round the field magnet coils and the flux produced thereby. If the field winding of a dynamo is supplied by a battery, there will be a definite current flowing and a definite flux produced.

What happens, however, in the usual commercial dynamo which has its field winding connected to the brushes, and therefore derives its current from the armature?

Should the dynamo voltage increase, we should expect the current through the field winding to increase, and this in turn would raise the flux and put up the generated voltage. If an increase in voltage produces a further increase, is there any logical stopping place? In other words, have we a kind of unstable equilibrium like a cone standing on its point? The answer is "No". The dynamo voltage will rise until a certain equilibrium point has been reached. The determination of this point is our present task.

If the generated voltage V is proportional to the flux "ϕ" produced by the field, and we know the relation between the field current "i" and this flux, then we can deduce the relation between field current and generated voltage. The graph will have the same form as the one just considered. We can therefore draw a curve as shewn in Fig. 52.

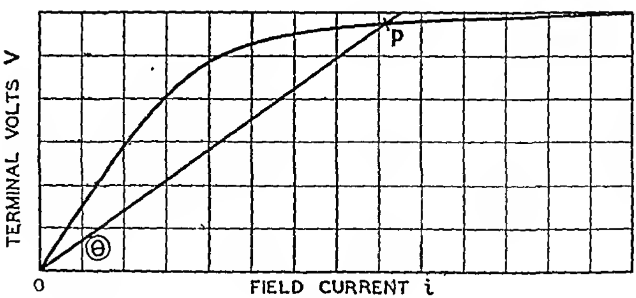


FIG. 52.—THE EQUILIBRIUM VOLTAGE OF A SHUNT WOUND DYNAMO.

At the same time we must bear in mind that the field current not only produces the generated voltage, but is circulated by it, according to Ohm's Law. In other words, the graph of V and I is a straight line as given by Ohm's Law: $V = Ri$ where R is the resistance of the field magnet windings.

This line, when drawn, must pass through the origin as one cannot have a current without volts—both must be zero together. Also the slope of the line or the Tangent of the angle θ must be R, i.e. $R = \text{Tan } \theta$.

The line OP and the curve both give the relation between i and V, one by the theory of dynamo voltage generation, the other by the ordinary Ohm's Law. The point P which is a point on both curves, must therefore be the working point, indicating by its position both the field current and the terminal voltage.

Regulation.

If the field resistance be varied, it will be necessary to draw a line having a different slope, and this will alter the point of intersection with the curve giving a higher or lower voltage. A regulating resistance is usually included in the field circuit of a D.C. generator to control the voltage. Increasing the field current raises the voltage and vice versa.

In a case where a generator supplies a current to a town over a long cable, the regulation enables the voltage at the town to be kept constant under varying load (current in amperes), although there is a variable loss of pressure due to the resistance of the cable.

Characteristics of Motors.

When a motor is running, electrical energy, measured in "units," is being turned into mechanical energy of motion. In Ohm's Law, where a current is driven through a conductor by a voltage according to the formula $E = Ri$, electrical energy is being turned into heat. It therefore follows that there is something more than Ohm's Law involved in the action of a motor.

When the motor is working, armature bars carrying currents are moving in the field of magnetic flux, driven by the "Mechanical Force" already described. In addition, the

mere motion of the conductors in the field generates an e.m.f. as in a dynamo, but whereas in a dynamo the generated e.m.f. drives the current through the armature windings and the external circuit, the opposite is the case in the motor.

> *The e.m.f. generated in a motor is a back e.m.f. and the supply voltage has to force the current against this back voltage.*

Since a generated voltage is proportional to the rate of cutting flux, it follows that the back e.m.f. is proportional to the motor speed, provided the field strength remains constant. In a shunt motor, where the field winding is a high-resistance winding shunted across the supply main, this is the case.

Shunt Motors.

The following sketch illustrates the principle of the shunt motor.

As the field winding of resistance R_f is shunted across the

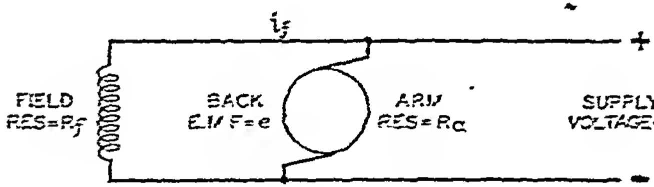


FIG. 53.—THE E.M.F.'S IN A SHUNT MOTOR.

supply main of voltage V, the current in the field coils i_f is given by Ohm's Law as $i_f = \dfrac{V}{R_f}$

In the case of the armature, however, it is the *difference* between the main voltage V and the back voltage E which drives the current i_a through the armature resistance R_a thus: $i_a = \dfrac{V - E}{R_a}$

The motor therefore runs up to such a speed that the voltage $(V-E)$ is just sufficient to send the right current through the

armature resistance. What do we mean by the "right current"? The force exerted by the armature in its motion is proportional to the current i_a, and therefore the current needed to keep up the motion is proportional to the load on the motor, i.e. the machinery which it happens to be driving. When the motor is driving nothing, or "Running Light" as it is called, it still requires a small armature current to overcome the friction of the bearings, the wind resistance and so on.

Example 12. The field strength and armature winding details of a 200-volt motor are such that it generates a back e.m.f. of 100 volts when running at 500 r.p.m. The armature resistance is ·1 ohm. Find the speed with different load currents up to 100 amps.

Speed-load Curve for a Shunt Motor.

Start with Ohm's Law for the voltage needed to circulate current through the armature. The voltage available for this purpose is $V-E$. This may be tabulated as follows:

I	R	$V-E$
10	·1	1
20	·1	2
30	·1	3
40	·1	4
50	·1	5
60	·1	6
80	·1	8
100	·1	10

The figures in the first column have been written down at random to give a list of currents up to 100 amps. The third column is obtained by multiplying currents by resistances. This gives the values of $V-E$. The V is 200, giving E by subtraction thus:

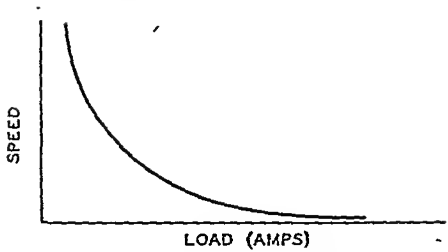


FIG. 55.—SPEED-LOAD CURVE OF A SERIES WOUND MOTOR.

Such motors are used for traction purposes and the following shows how a tram with two motors is controlled.

The two series motors are first put in series and then in parallel still being series motors. (Fig. 56).

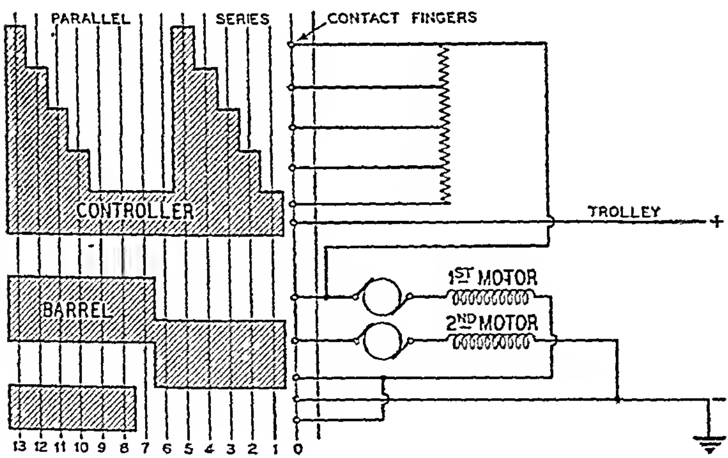


FIG. 56.—CONTROL DIAGRAM OF TRAMCAR WITH TWO MOTORS.

Interpoles.

Many dynamos and motors are fitted with small magnet poles between the main ones. These are called interpoles. They carry the armature current, having a few turns in series with the armature. (See Fig. 57).

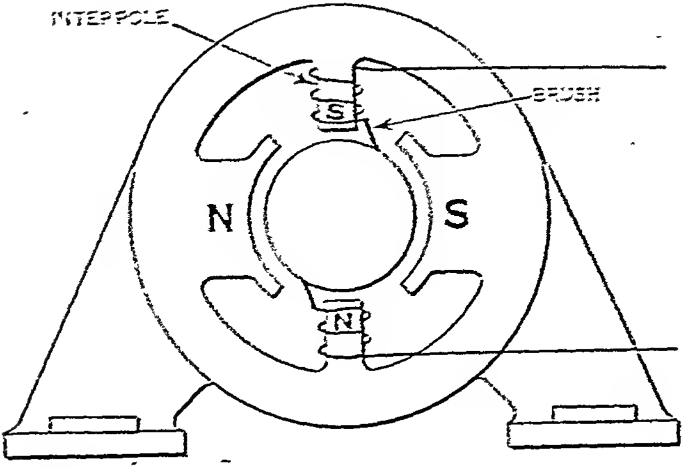
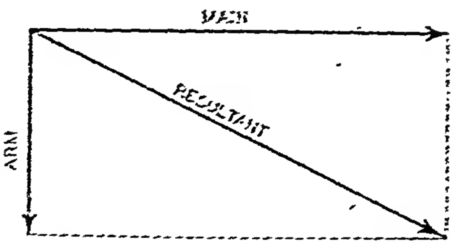


FIG. 57.—INTERPOLES.



Motor Control.

SHUNT MOTORS. When the motor armature is stationary, no back e.m.f. can be generated, and if the main switch were

closed, putting the full main pressure across the armature, the resulting heavy current would blow fuses and possibly damage the cables and switchgear. To obviate this, a variable resistance is connected in the armature circuits, and arrangements provided by which it is cut out, either by hand or automatically, as the speed increases. The field winding should be fully energised from the first moment, to give the biggest possible back e.m.f. and starting torque.

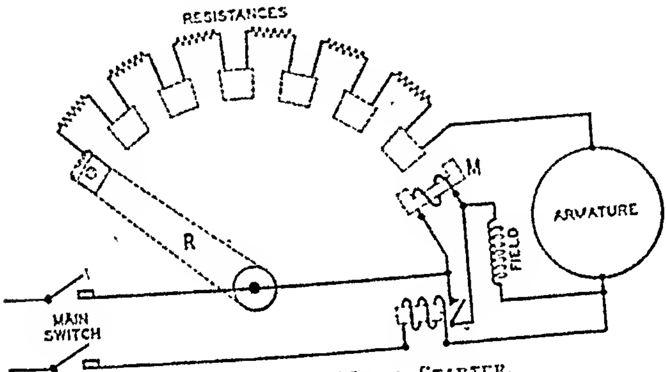


FIG. 59.—SHUNT MOTOR STARTER.

The resistance must be re-inserted in the armature circuit when the motor is stopped, so that it is ready for starting when next required, and in the usual type of motor starter shown in the following sketch, this is done automatically, by means of a return spring. While the motor is running, the starter switch arm is held in position against the spring, by an electro-magnet.

Since alternating current is now so common, alternating current motors are gradually taking the place of direct current ones. The simplest of these as regards its construction is the induction motor. It is like a transformer in which the mechanical forces make the secondary coils move.

CHAPTER X

SOUND AND SPEECH

THIS is a suitable place to explain the telephone. Sound is a rapid to and fro motion or vibration in the air. The number of complete to and fro movements or cycles per second is called frequency. A low frequency sound has a low tone and a high frequency a high tone or pitch.

Most musical instruments such as a violin send out the main tone or fundamental note together with vibrations whose frequencies are whole multiples of the fundamental, when sounding any one musical note. These higher components are called harmonics and the number and strength of them gives the tone its musical "quality".

In speech every consonant and every vowel has its own wave form consisting of—it may be said—many harmonics. In point of fact, the air particles execute complex vibrations and this way of expressing the whole movement as the sum of so many different harmonics is due to Fourier. Since each harmonic is a simple sine wave, it reduces the whole study to that of simple sine waves.

In the original "Bell" Telephone, a long horseshoe magnet

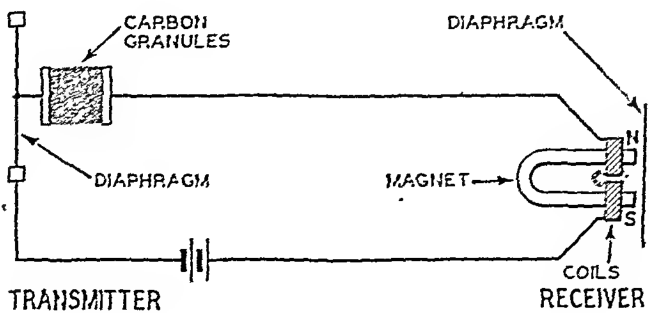


FIG. 60.—TELEPHONE TRANSMITTER CIRCUIT.

has coils of wire round the ends and a disc or diaphragm of iron is supported so as to be near but not to touch the coils. (See Fig. 60). A current flows through the coils and either assists or weakens the magnet and so varies the pull on the diaphragm. As the current is varied at the transmitter by the speaker's voice, the receiver diaphragm varies in accordance with the distant air vibrations and so reproduces the sound.

The transmitter is a small box full of carbon granules with a diaphragm in front. When this moves it varies the pressure on the granules, makes their resistance larger or smaller and so varies the battery current which flows through them.

In calculations on telephone systems, the engineer usually considers one sine wave frequency at a time from the lowest to the highest. He therefore chiefly needs to be able to calculate the currents and voltages for a simple steady sine wave of any given frequency.

This is the study of alternating currents.

CHAPTER XI

ALTERNATING CURRENTS

ALTERNATING currents flow first in one direction then in the other. If a direct current is likened to a steadily turning wheel, an alternating current is like the balance wheel of a watch. In radio work the speech currents as well as the high frequency currents are all alternating and they are often part of a total current which includes some direct current too. This is the case in a valve. Historically the alternating currents which were first studied were produced by generators.

Generation of Alternating Currents.

If a dynamo is made without a commutator, wires may be taken from the armature winding to plain brass rings instead. These rings are insulated from the shaft to which they are firmly fixed. Brushes make contact with the "slip rings," as they are called, and the brushes lead the current round the outside circuit. Since each armature wire passes first under a North and then under a South pole the current in the armature conductors reverses or "alternates" rapidly and since there is now no commutator, to put these reversals "right," as it were, the current round the outside circuit flows first in one direction and then in the other. It is alternating. The current starts from zero, goes round the circuit one way rising to a maximum, and then dies away to zero. It then reverses, rises to a maximum in the other direction, and falls to zero ready to start out in the first direction again. That is *one cycle.* The number of cycles per second is called the *Frequency*. The "Grid" power supply of Britain is at 50 cycles per second. That is 50 maxima in each direction or 100 reversals per second.

The alternating current generator or alternator has come into its own. The reason is that the alternating current

may be made to produce another alternating current at quite a different voltage by means of a simple transformer.

The Transformer.

If a coil of wire is wound round an iron core and another coil wound round this again, this core and two windings constitute a transformer.

One coil is connected to the alternator and alternating current flows through this winding which is called the primary.

The primary inductance must not be so low that the primary coil forms a heavy shant across the circuit, taking a big current and lowering the applied voltage.

With the secondary coil disconnected, the primary coil takes a current when it is connected to a source of alternating voltage.

The current magnetises the core first in one direction then in the other. The result is an alternating flux. This flux generates a back e.m.f. in the primary turns because it is a changing flux. The back e.m.f. balances as it were the applied e.m.f. But there is an e.m.f. induced in each turn of the secondary coil. If the secondary has more turns than the primary winding, the total secondary voltage will be greater than the primary e.m.f., i.e. than the applied voltage.

It is impossible to study alternating currents without understanding the relations between current and voltage first in "Inductance" and then in "Capacity," for these two, while they complicate the subject, make it possible for the electrical engineer to evolve practically any combination to suit the end he has in view.

Inductance and Capacity.

When current is increased or decreased in a coil, a voltage due to self-induction is generated in the coil. If the current is rising in strength, the induced e.m.f. acts in such a direction round the turns as to hinder the flow of current; but if the current is decreasing, the induced e.m.f. acts in such a direction as to keep the current flowing along the wires of the coil. This phenomena is explained by the two facts that *Current Causes Magnetic Flux, and Changing Magnetic Flux causes*

or generates voltage round the lines of flux. Therefore changing current in a coil generates voltage.

Expressed mathematically we have

$$E \propto \frac{di}{dt} \text{ meaning } \frac{\text{A small increase in } i}{\text{A small increase in } t}$$

but E depends on the number of turns, size of coil, shape and also material of core; air, iron, etc. It is usual to say that if one ampere per second rate of current change causes 1 volt to be induced in the coil, then we have 1 henry. So if the coil is of inductance L henrys the formula becomes

$$E = L \text{ times rate of change of } I$$

$$\text{or } E = L\frac{di}{dt} \text{ which means the same.}$$

It is important for the beginner to realise that a *back* e.m.f. is generated *in* the turns of the coil when the current *increases* in the coil.

At the same time, once that is clear, one may go on to use the E in the formula to represent the applied e.m.f. needed to overcome the induced back e.m.f. Then the minus sign often used when E represents *back* e.m.f. should not be in, when it represents the applied e.m.f. The formula $E = L\frac{di}{dt}$ suggests that one should examine the current wave and note its rate of change. An easy and important case is a sine wave lasting 2π seconds for 1 cycle. It is $I = \text{Sin } t$. This curve drawn on a true scale of height 1 inch and base 2π inches per cycle starts off at 45°.

As $\tan 45° = 1$ the slope is 1 at its greatest slope, and $\frac{dI}{dt}$ is simply 1 times Cos (t). This means $\frac{dI}{dt}$ is just Cos (t), a wave of equal height to sin (t) but 90° advanced in phase. If now we take not 1 cycle in 2π seconds but 1 cycle in 1 second, everything is speeded up 2π times and all rates of change are 2π times faster. The way of writing 1 cycle per second is Sin $2\pi t$ and the new slope is 2π times Cos $2\pi t$. If we have f cycles per second we write it sin $2\pi ft$ and the new slope is $2\pi f$ Cos $2\pi ft$. The multiplier $2\pi f$ comes in so often that we use a separate letter w for it. $\omega = 2\pi f$.

The Slope of a Sine Curve.

Since it is fundamental to know the rate of change of current in a coil and of voltage on a condenser in order to calculate the coil voltage or condenser current, the student may wish to have proof that the rate of change of Sin θ is Cos θ. That is to say, since the slope of Sin θ varies along the curve, if, for example, it is required that the slope be, at say, $57\frac{2}{11}^{\circ}$ where $\theta = 1$ radian, put 1 in Cos θ and Cos 1 or Cos $57\frac{2}{11}^{\circ}$ which is about ·87, so the slope of sin θ is ·87 when the angle is 1 radian.

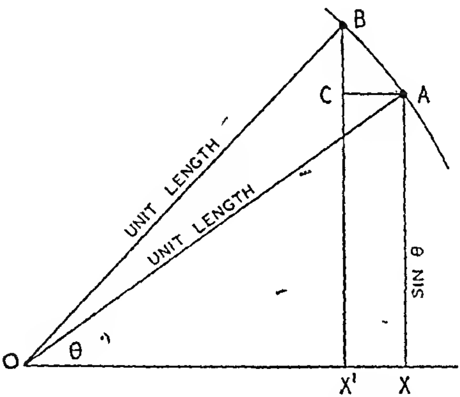


Fig. 61 —The Slope of a Sine Curve

To prove that the rate of change of Sin θ is Cos, θ in Fig. 61. Draw OA to form the angle θ. The perpendicular AX measures sin θ if we make $OA = I$.

Now if the angle θ increases slightly from A to B, the increase of angle is $\frac{AB}{OB}$, which is the way angles are measured in radians: it is $\frac{\text{arc}}{\text{radius}}$. Here, as the radius is 1 the angle is AB.

The new value of the Sine is $\frac{BX^1}{1} = BX^1$ and the increase BC is the increased sin for an agle increase of AB.

The ratio $\frac{BC}{AB}$ is the $\frac{\text{increase of Sin } \theta}{\text{increase of angle } \theta}$ and so is the desired rate of change or "slope" of a sine curve when plotted out as a wave. The increase should be small in this drawing and then AB becomes like a straight line and $\frac{CB}{AB}$ becomes Cos CBA, which is Cos θ, because AB leans at an angle θ to the vertical.

Measurement of Sine Wave Currents.

Sine wave currents are usually measured as the current which would cause the same heating effect as a direct current. Since the heating is the square of current multiplied by the resistance, we need Sin ^2x. From easy trigonometry Sin ^2x is seen to be $\frac{1}{2}-\frac{1}{2}$ Cos.$2x$, because Cos $2x = 1 - 2$ Sin ^2x.

In $\frac{1}{2}-\frac{1}{2}$ Cos $2x$ the $\frac{1}{2}$ Cos $2x$ is a double frequency wave and contributes nothing to the average value of the Sin ^2x which is $\frac{1}{2}$. The direct current which when squared to give the heating effect equal to the alternating current, i.e. equal to $\frac{1}{2}$ is $\sqrt{\frac{1}{2}}$ and this is $\sqrt{\frac{2}{2} \times \frac{1}{2}} = \frac{\sqrt{2}}{2}$

$= \frac{1{\cdot}414}{2} = {\cdot}707$ amps.

Thus a ·707 amp direct current is as good as Sin wt which peaks at 1 amp. This ·707 amp is the Root of the Mean of

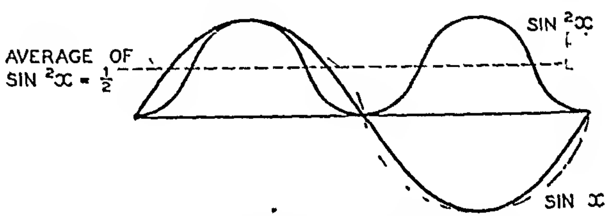


Fig. 62.—The Square of a Sine Curve.

the Square of sin x or RMS value. Therefore the RMS value of a voltage or current, the "commercial" value, is ·7 of the Maximum for a sine wave.

Graphically when $\sin x = \frac{1}{2}$ then $\sin^2 x = \frac{1}{4}$. When $\sin x = \frac{3}{4}$ then $\sin^2 x = \frac{9}{16}$ which is less and the curve is as seen in Fig. 62.

Alternating Currents with Inductance.

With an alternating current Sin wt the voltage required to drive it through one henry is ω times Cos wt so we see that the voltage wave is 90° in advance of the current wave. The lagging current on an inductance is most important. With the lag there is the amplitude relation that when:

$$\text{Current} = \text{Sin } wt$$
$$\text{Voltage} = w \text{ Cos } wt$$

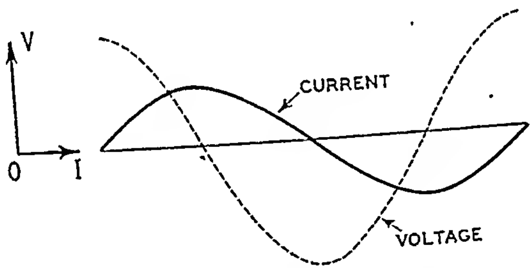


FIG. 63.—CURRENT AND VOLTAGE ON A PURE INDUCTANCE.

When it is not merely Sin wt, which means a wave with a peak of 1 amp. but I sin wt with a peak of I amps. then

$$V = wI \text{ Cos } wt.$$

Since this is for 1 henry, and in general the inductance is L henries, we have $V = LwI$ Cos wt.

The current is I Sin wt, but as Cos and Sine waves are the same shape with a time or phase difference, we have

$$\frac{V}{I} = Lw \text{ as regards size.}$$

This calculates current from voltage with any inductance at any frequency.

Here are some easy examples of this:

Example 13. A 40 henry coil carries 1 milliamp. at 100 cycles per second, what is the voltage needed to send that current through such a choke?

Here $f = 100$ so $2\pi f = 628$.

Since $L = 40$ always to be henries and $I = \frac{1}{1000}$ amp. we have

$$E = LwI = \frac{40 \times 628}{1000} = 25.12$$

so the answer is 25 volts. If the milliamp. was a wave of maximum value 1 milliamp., then the voltage is 25 volts maximum, but if it is 1 milliamp. heating value, i.e. RMS such as would make a meter read 1 m.a., then the voltage is 25 volts RMS too.

Example 14. Again a 1 millihenry coil carries 1 amp. at half a megacycle, what is the voltage?

For an amp., by the way, it would be a small transmitter. Here again $E = LwI$ and I is one, so

$E = \frac{1}{1000} \times 2\pi \times \frac{1 \times 10^6}{2} = 3141$ times the 1 amp. $= 3141$ volts.

Here we see that, apart from the 90° lag of current the coil seems to have 3141 ohms. We say it has 3141 ohms not of resistance but *reactance*.

Reactance.

The product Lw, then, for a coil is so many ohms and once this reactance is calculated we use it just like Ohm's Law, current equals voltage divided by reactance.

1 volt is applied to a coil of $\frac{1}{6}$ millihenry. The current is a steady carrier at 1 megacycle.

Then $V = 1$

$$w = 6{,}280{,}000$$

$$L = \frac{1}{6000}$$

Put these in $V = LwI$ so that $I = \frac{V}{Lw}$ and $I = \frac{6000}{6280000}$

$= \cdot 95$ milliamps.

The best way is to regard Lw as so many ohms at that frequency and work like Ohm's Law, where $I = \frac{V}{\text{ohms.}}$

The reactance as Lw is called, goes up with frequency, and there is too the phase difference here which one doesn't get with a resistance.

Circuit containing Inductance and Resistance in Series.

Here, because the two are in series, the current is the same but *not* the voltages V_L across the inductance and V_R across the resistance. They are not in the same phase and may not be the same size. The total voltage at any instant on the whole circuit is, however, the sum of the values of V_L and V_R at that instant.

Thus the two waves need adding. To add two waves moment by moment we go back to the rotating vectors which in mathematics are always used to generate the waves. Thus in Fig. 64 V_L is the vector representing the wave of voltage on the coil and V_R is the vector representing or drawing the wave of voltage on the resistance. The total voltage is V total, and is the diagonal of the rectangle because these rotating lines always combine by addition like vectors. The proof is easy. See Fig. 65. Suppose OA and OB are two such vectors, which generate or represent sine waves.

A sine wave is drawn by a rotating vector. At the moment shown, S^1A is the value of the voltage—the instantaneous value of the voltage *represented or generated by the line* OA.

Similarly the voltage represented at the moment by OB is BS.

If one completes the parallelogram $OBPA$, then the height of P is by Geometry $AS^1 + BS$, which makes P by its height represent the true sum of the instantaneous voltages. Thus the vector OP by the height of P represents the sum of the heights of A and B, so this vector is the sum of the vectors OA and OB. The proof is that $PQ = BS$ and $QT = AS^1$.

Thus $BS + AS^1 = PT$.

The result is that one always adds vectors in this way. (See Fig. 66).

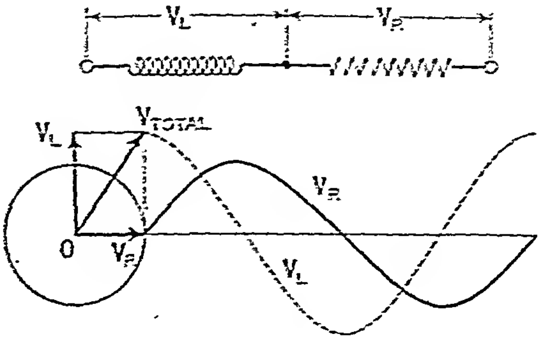


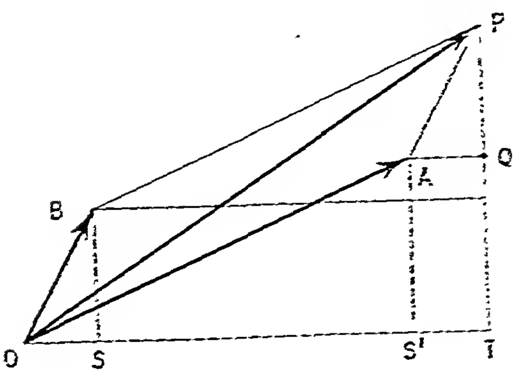
FIG. 64.—CURRENT AND VOLTAGES IN AN INDUCTIVE CIRCUIT.

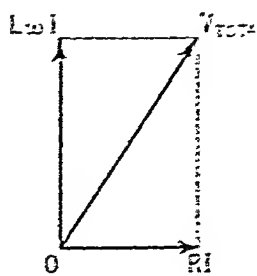
In the present case $V_R = RI$ by Ohm's Law and $V_L = L\omega I$., so as these are at right angles, we use Pythagoras and V Total $= \sqrt{R^2I^2 + L^2\omega^2I^2}$
Bracket out I and we have

$$V = I\sqrt{R^2 + L^2\omega^2}$$

now dividing all along by $\sqrt{R^2 + L^2\omega^2}$

$$I = \frac{V}{\sqrt{R^2 + L^2\omega^2}}$$





Condensers.

A condenser charges up to a higher voltage as more and more current is sent into it by an applied voltage. The pressure on its terminals depends on the charge in *Amps. and Seconds* or Coulombs, and 1 amp. for 1 sec. charges 1 Farad to 1 volt. Most condensers are a small fraction of a farad. A larger condenser needs more coulombs to charge it to the same voltage. In general, $Q = CV$ where Q = quantity of electricity in coulombs, C is in farads. With a condenser, then, it is I equals C times rate of change of Voltage.

Now compare this with

$$E = L \text{ times rate of change of } I$$

for a coil. The two are the same but for interchange of E and I mathematically, because L and C are just constants, though different physically.

If then $E = L\frac{di}{dt}$ for a coil gives $E = LwI$ for a sine wave with lag of *current* then $I = C\frac{dE}{dt}$ gives $I = CwE$ with lag of *voltage* for a condenser.

Reactance of a Condenser.

Reactance is $\frac{E}{I} = \frac{1}{Cw}$ in this case. Thus the reactance of a condenser is $\frac{I}{Cw}$

Since $V = L\frac{di}{dt}$ results in Current lagging 90° in the case of a coil, so the formula

$$I = C\frac{dv}{dt} \text{ results in Voltage lagging } 90°$$

in the case of a condenser. It is often said that in a condenser the Current Leads 90° ahead of the voltage. That is saying the same thing.

The reactance of a condenser is best understood by an example.

What is the reactance of a 2μf. condenser at 800 cycles? The question and answer are well worth remembering, for reasons that will be described.

Here C is $\frac{2}{10^6}$ and $w = 2\pi \times 800 = 5{,}000$ nearly.

So reactance $= \frac{1}{Cw} = \frac{1}{\frac{2}{10^6} \times 5000}$

Invert the divisor $\frac{2}{10^6}$ thus:

$$\frac{1}{5000} \times \frac{10^6}{2} = \frac{1000000}{10000} = 100.$$

So it is 100 ohms. This means that at that frequency 20 volts would give a current of $I = \frac{E}{\text{Reactance}} = \frac{20}{100}$ which is $\frac{1}{5}$ ampere.

Notice now the result of a different frequency in the case of coil and condenser.

The Variation of Reactance with frequency and size of components.

If with an inductance—and in discussing inductance one ignores resistance to make it clear what inductance is and does—we double the frequency, then because it is Lw that is L multiplied by w, the reactance is doubled.

Also a double size of inductance gives double reactance with the same frequency. With Condensers it is quite different. Here it is $\frac{1}{Cw}$ and as $\frac{1}{10}$ is less than $\frac{1}{5}$ or $\frac{1}{2}$ then $\frac{1}{Cw}$ is a smaller reactance in ohms if Cw is *larger*. Thus a larger condenser or a higher frequency lowers the reactance. If then 2μf. at 800 cycles is 100 ohms, it follows that 4μf. at 800 cycles is 50 ohms, and $4\ \mu$f. at 8,000 cycles is 5 ohms.

Making of Inductances.

If a large number of henries is needed, the method of construction is to use an iron core of stampings and wind many turns. These stampings are often as shown in Fig. 67.

They are also used for transformers. The use of a number of them saves the generation of large currents in the iron core. These would be set up because iron is a conductor of elec-

tricity. The stampings are each insulated to reduce the eddy currents.

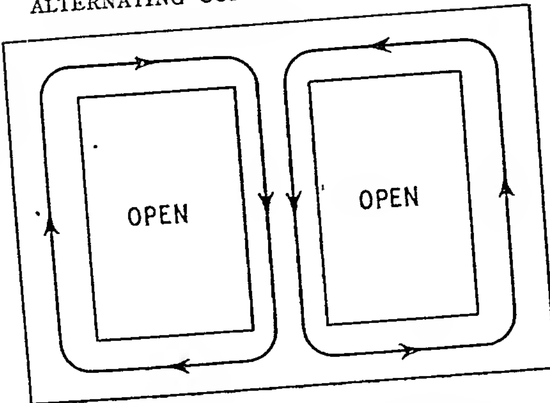


FIG. 67. TYPICAL TRANSFORMER STAMPING.

The coil is wound round the centre bar. If with a bundle of a certain size stampings, one ampere turn gives 400 lines of flux, say, and there are "n" turns, then the flux for 1 amp. is $400n$ supposing we are on the straight part of the magnetisation curve for the iron. If the amp. died away in a second the rate of flux change would be $400n$ lines per second so $\frac{400n}{10^8}$ volts would be induced per turn. The total volts would be $\frac{400n^2}{10^8}$ and this is the number of henries, as it is worked out for 1 amp./sec. current change, making $\frac{di}{dt} = 1$ in the formula $E = L\frac{di}{dt}$ so as far as arithmetic goes $E = L$ and we have worked out E and so found L.

Radio Coils.

In radio work all the flux does not go round the same path as it nearly does in an iron choke, so all the flux does not cut all the turns. Yet the coil has inductance and the n^2 comes in. Double the turns for the same shape and size of coil and the inductance is quadrupled.

Inductance, then, depends on the square of the turns and on the size of coil and the shape, i.e. ratio of length to diameter. Figures are given in various data books.

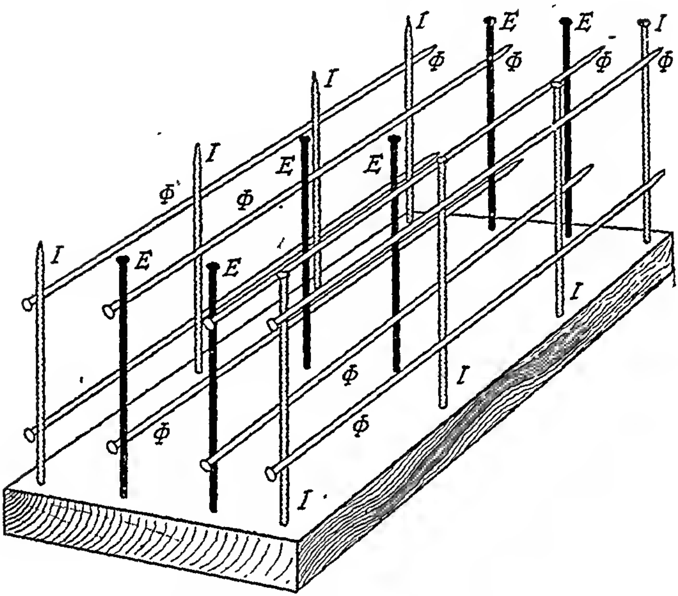


FIG. 69.—MODEL, MADE FROM PINS, ILLUSTRATING RADIO WAVE IN SPACE. THE WAVE IS MOVING TO THE RIGHT.

the wave empty. These currents are not a flow of electrons, as the current in a conductor is, but there is a ground current in the earth from the front to the back of the wave; an electronic current, and this with the displacement currents forms a "coil" of one turn which magnetises the space in the body of the wave. A magnetic flux is thus produced. The flux is horizontal, and the wave spreads in circles round the broadcasting station, like ripples when a stone is thrown into a pond.

Since the wave is moving, the moving flux generates a voltage in space, just as the flying poles of an alternator generate voltages in the stationary wires on the frame of the machine. These voltages must, by Fleming's rule, be at right angles to the wave motion, and to the lines of magnetic flux. The lines of induced voltage are, therefore, vertically downwards; and now the circle of reasoning is complete.

This is the voltage E with which we began, represented by the vertical pins pointing downwards in the body of the wave. Hence the wave can travel and is self-sustaining. As it travels and spreads it grows weaker.

One question often asked by the enquiring student is this: "Why is there a factor of $\frac{1}{4\pi \times 9 \times 10^{11}}$ in the formula for the capacity of a plate condenser?" The formula referred to is $C = \frac{A}{4\pi d \times 9 \times 10^{11}}$ farads. A is the area of a plate (in sq. cms.), and d their distance apart in cms.

The above explanation of a wave can be used to answer the question. Let the wave be supposed to be contained between a "floor" and "ceiling" of a metal of no resistance and let the sides of the tube be made of a material of perfect magnetic properties arranged in a horseshoe, the wave to travel along an axis rather like the axle of a magneto, i.e. in between the poles or like an Anderson shelter. (See Fig. 70).

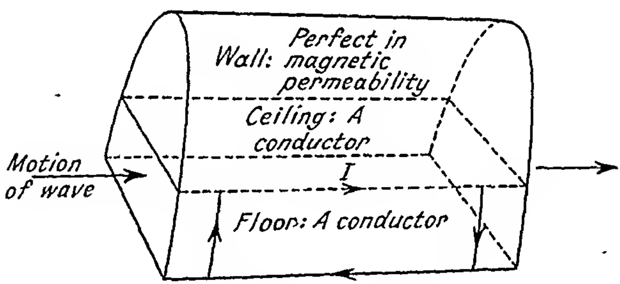


FIG. 70.—RADIO WAVE TRAVELLING DIRECTIONALLY IN SPACE.

The square tube may be one centimetre square in section rather than as big as an "Anderson" for ease of calculation. Suppose the voltage E is one volt between top and bottom of the tube. This volt charges 186,000 miles of space per second, which is 3×10^{10} sq. cms. of plate area as the wave runs along a strip 1 cm. wide. It makes a condenser of value $\frac{3 \times 10^{10}}{4\pi \times 9 \times 10^{11}}$ i.e. $\frac{1}{120\pi}$ farads.

If $Q = CV$ then the quantity per second of electricity is $\frac{1}{120\pi}$ coulombs for 1 volt, so there is a current of $\frac{1}{120\pi}$ amp. flowing along the "ceiling" in a forward direction, back along the floor and up at the back of the wave as shown in Fig. 70. This is the current I in Fig. 69.

This constitutes one turn, so there is $\frac{1}{120\pi}$ ampere-turns magnetising the space. Since $\mu = 1$ for air, and the relation between flux and ampere-turns is then $\beta l = \frac{4\pi}{10}$ amp.-turns we have a flux of $\frac{4\pi}{10} \times \frac{1}{120\pi} = \frac{1}{300}$ because "l" is 1 cm. between the sides of the tube for the length of path of the flux.

Since the wave velocity (the velocity of light) is 3×10^{10} centimetres per second, the rate of generation of flux is 10^8 lines per second which always generates a volt. This is the voltage which we began with.

The crucial point is that the figure $\frac{1}{4\pi \times 9 \times 10^{11}}$ for the capacity of a centimetre cube of free space, has produced the right result in the case of a travelling wave. The figure 3×10^{10} cms. per second for the velocity of light is found in more ways than one. The earliest was observation on Jupiter's moons. Therefore, the factor is correct, and is proved so.

When a wireless wave is picked up on an ordinary vertical aerial, it is the electric voltage E in the wave which counts. On the other hand, a frame aerial works because the magnetic flux Φ in Fig. 69 cuts the turns. This aerial then gives maximum strength when its plane is directed towards the station so that the expanding rings of flux cut the turns.

CHAPTER XIII

RESONANCE CURVES

Series Resonance.

RESONANCE is found in nature apart from electricity. It is in sound, and also in mechanical vibration as in motor engines. Consider a series resonant circuit as shown in Fig. 71 consisting of coil, condenser and resistance in series.

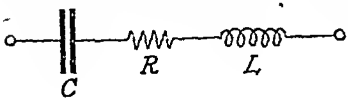


FIG. 71.—DIAGRAM FOR CONDENSER (C), RESISTANCE (R), AND INDUCTANCE (L) IN SERIES CIRCUIT.

The voltage on the coil and that on the condenser are always in opposition. They are in opposition, that is, moment by moment, at every part of every cycle, whatever the frequency, as long as the frequency and voltage are steady. The coil and condenser voltages are equal in resonance only.

The current in every part of the circuit is the same at any moment and so one must draw voltage vector diagrams. The resistance R usually represents the D.C. ohmic resistance of the coil together with the losses at the high frequency.

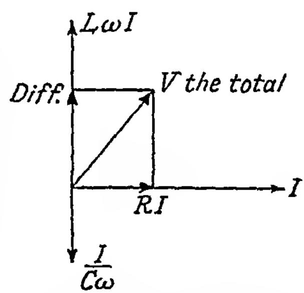


FIG. 72.—VECTOR DIAGRAM FOR L, C AND R IN SERIES.

The vector diagram is as shown in Fig. 72.

The total voltage V is given by

$$\sqrt{\left\{RI\right\}^2 + \left\{L\omega I - \frac{I}{C\omega}\right\}^2}$$

or to give it its usual form, the current for a given voltage V is:

$$\frac{V}{\sqrt{R^2 + \left\{L\omega - \frac{1}{C\omega}\right\}^2}}$$

It may be asked: "Why bother about the 10 ω resistance at all?"

The reason is that round about the resonant frequency this resistance makes a lot of difference. When, for example, $L\omega - \frac{1}{C\omega}$ is also 10 ohms like the resistance, the total impedance is found from $\sqrt{10^2 + 10^2}$ to be 14·14 ohms, making the current fall to 70·7 per cent of the full $\frac{E}{R}$ value at resonance.

This incidentally is a figure much used in experiments on the losses in resonant circuits. It is possible to plot a "general" curve thus:

By writing a new variable, Ω, for

$$\frac{\text{frequency used}}{\text{resonant frequency of circuit}}$$

one can get a very simple expression for the current flowing, as a fraction of the current at resonance, which is simply $\frac{E}{R}$

(One must be careful not to confuse Ω here with the same symbol used for ohms.)

Parallel Resonance.

Here the current in the lead to the parallel circuit is small at frequencies round about resonance, and one may, therefore, say that the impedance of the circuit is high. Neglecting losses, the impedance at resonance is infinite, but losses in —say—the coil, make the coil current lag at an angle behind the applied voltage which is not quite 90°. The two currents, the coil and condenser currents can never therefore add up to zero, and the circuit cannot have an infinite impedance. To find out how big its impedance at the resonant frequency really is, in a particular case, one uses a simple formula developed as follows: (See Fig. 73).

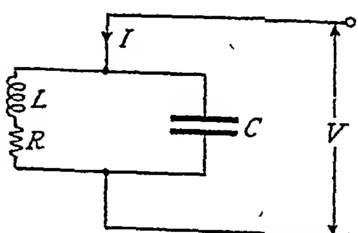


FIG. 73.—A COIL AND CONDENSER IN PARALLEL.

The R represents the D.C. resistance of the coil, to which must be added resistance due to losses at high frequency.

Losses in Coils.

At high frequencies there is a tendency for the current to flow along the outer portions of a wire and not much through the inner part. The current flows in the "skin" only, and this is called skin effect. The greater current density in the outer layers calls for a larger voltage to drive the current through, and so the effective resistance of the wire is greater. There are special stranded wires used in order to afford as much surface as possible.

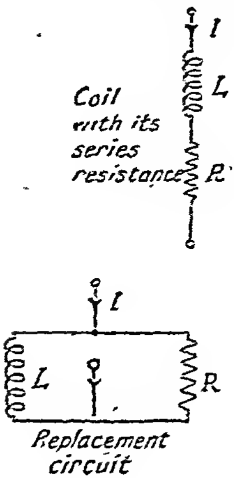


FIG. 74.—REPLACEMENT OF COIL BY EQUIVALENT CIRCUIT WITH PARALLEL RESISTANCE.

The coil with L and R in series should now be replaced by a combination of a *perfect* inductance and a high shunting resistance in parallel, which would allow the same value of current to flow, as in the real coil with its series resistance R, and also make the angle between current I and voltage V the same for the two, as in Fig. 74.

This is a separate little problem and the current I used here to make the R and L in series, into a coil and resistance in parallel, is not the I in the common lead to the resonant circuit.

To use subscripts such as in I_1 or I_2 in separate problems is confusing to a beginner, and is avoided here.

If R is a small fraction of $L\omega$ (even if it is as big as $\frac{1}{4}$) then the vector voltage V on the coil is not sensibly increased in length by the resistance drop RI so the V on the coil in the series circuit can be supposed equal to V in the parallel case. Also in the parallel case the current through Z will not lengthen the vector current I going in to the circuit if Z is, say, as little as 4 times $L\omega$; so the ratios of currents to voltages depend chiefly on $L\omega$. This means the parallel circuit replacing the series has the same inductance.

The phase angles of the two circuits should be the same, and so should the vector diagrams in Fig. 75.

Let us study the phase angles.

The phase angle for the series circuit shows the lag of current; $\left(\tan\theta = \dfrac{L\omega}{R}\right)$ where voltages are considered, and for the parallel circuit where one must consider currents,

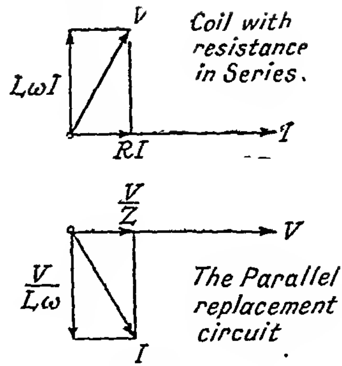


FIG. 75.—VECTOR DIAGRAMS FOR COIL AND ITS REPLACEMENT.

$$\tan\theta = \frac{\dfrac{V}{L\omega}}{\dfrac{V}{Z_2}} \text{ which is } \frac{Z}{L\omega}\text{; so, if they are to be the same,}$$

$$\frac{L\omega}{R} = \frac{Z}{L\omega} \text{ from which } Z = \frac{(L\omega)\,(L\omega)}{R}$$

To get the same effect with Z as with a series resistance R at the resonant frequency, since $L\omega$ is equal to $\dfrac{1}{C\omega}$ at resonance, one puts $\dfrac{1}{C\omega}$ for one of the $L\omega$'s above and $Z = \dfrac{L}{CR}$ which is called the "dynamic resistance" of the parallel circuit. It is the impedance at resonance, because one may put the new combination in the tuned circuit as shown in Fig. 76.

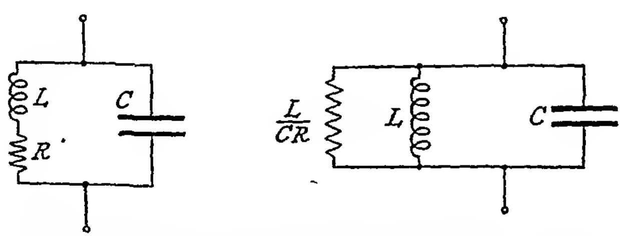


FIG. 76.—THE PARALLEL RESONANT CIRCUIT AND ITS FINAL EQUIVALENT AFTER REPLACEMENT.

The L and C on the right are together of infinite impedance at resonance, so the impedance of the whole circuit, which is a replacement for the true one on the left, is $\frac{L}{CR}$; at resonance, that is, and not at other frequencies. How one defines resonance here is another matter!

The formula $\omega = \frac{1}{\sqrt{LC}}$ is usually near enough.

As an example, let $L = \frac{1}{4}$ mh. and $C = \cdot 0001$ mf. and $R = 10\omega$. Then the impedance Z of the circuit is $\frac{1000000}{\cdot 0001 \times 10} \times \frac{1}{6000} = 167{,}000$ ohms (approx.): a surprisingly high figure. To demonstrate this, one should use a tetrode or H.F. Pentode as described under "Experiments".

"Magnification."

This is a factor giving the voltage across a coil in tune divided by the voltage with no condenser. It depends on the resistance and it is well to know the relation.

Suppose a series circuit has a valve grid and filament connected across the coil and the circuit is in resonance. Then without the condenser, the voltage would be the applied V. With the condenser the current is $\frac{V}{R}$ and the voltage on the coil $\frac{VL\omega}{R}$ or $\frac{L\omega}{R}$ times the applied voltage.

The $\frac{L\omega}{R}$ is called the Q of the circuit. The R is the D.C. resistance plus the losses, and any losses in the condenser (say 10 ohms in series with its reactance, for example) can be added to the coil loss to give a total R. When, by the use of a valve of extra high impedance, one pushes a current through a parallel resonant circuit tuned to resonance, the voltage developed across the coil is $\frac{L}{CR}$ times I where I is the current. If the condenser is taken away the voltage is $L\omega I$. The ratio is again $Q = \frac{L\omega}{R}$ as before.

The Generalised Resonance Curve.

It is possible to plot one set of curves which cover all series circuits. Take the current in the series circuit

$$I = \frac{E}{\sqrt{R^2 + \left\{ L\omega - \frac{1}{C\omega} \right\}^2}}$$ and consider current as a fraction of the current at resonance which is $\frac{E}{R}$. This is $\sqrt{1 + \frac{1}{R^2}\left\{ L\omega - \frac{1}{C\omega} \right\}^2}$

Also consider Ω as the frequency, divided by the resonance frequency, or with the 2π's, $\frac{\omega}{\omega_o}$ where ω_o is the number of radians per second for the resonance frequency. That is $\omega_o = \frac{1}{\sqrt{LC}}$; or, $\omega\sqrt{LC}$ is the new Ω. Now put $\frac{\Omega}{\sqrt{LC}}$ instead of ω in the formula and we have:

$$\text{Current ratio} = \frac{1}{\sqrt{1 + \frac{1}{R^2}\left\{\frac{\Omega L}{\sqrt{LC}} - \frac{\sqrt{LC}}{\Omega C}\right\}^2}}$$

This becomes $$\frac{1}{\sqrt{1 + \frac{L}{CR^2}\left\{ \Omega - \frac{1}{\Omega}\right\}^2}}$$

and if we put an ω_o in the numerator and denominator of $\frac{L}{CR^2}$ it is seen to be $\frac{L\omega_o}{R} \times \frac{1}{C\omega_o R}$ or, $\left(\frac{L\omega_o}{R}\right)^2$ which is Q^2 meaning the Q at resonance. Thus the formula reduces to the simple and comprehensive one:

$$\frac{\text{Current}}{\text{Current at Resonance}} = \frac{1}{\sqrt{1 + Q^2\left(\Omega - \frac{1}{\Omega}\right)^2}}$$

From which it is seen that when $f = \frac{5}{4}$ of the resonance frequency, there is the same value of current as at $\frac{4}{5}$ of the resonance frequency, and so on.

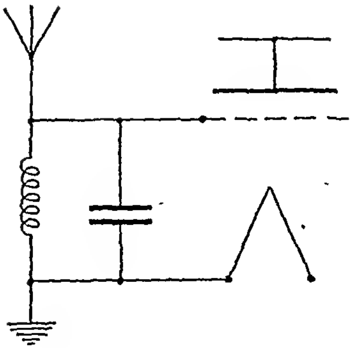


FIG. 77.—PARALLEL RESONANCE IN A RECEIVER CIRCUIT.

The Parallel Circuit in Practice.

A common question is, "If a parallel circuit acts like a high resistance at resonance, why is it used in place of a resistance in the circuit?"

The Circuit is shown in Fig. 77.

The condenser C and coil L are not themselves in resonance when the loudest music is heard, because the aerial has capacity to earth. The loudest signal is when C is a little under the value found by $\frac{1}{\sqrt{LC}}$; then the circuit "looks like"

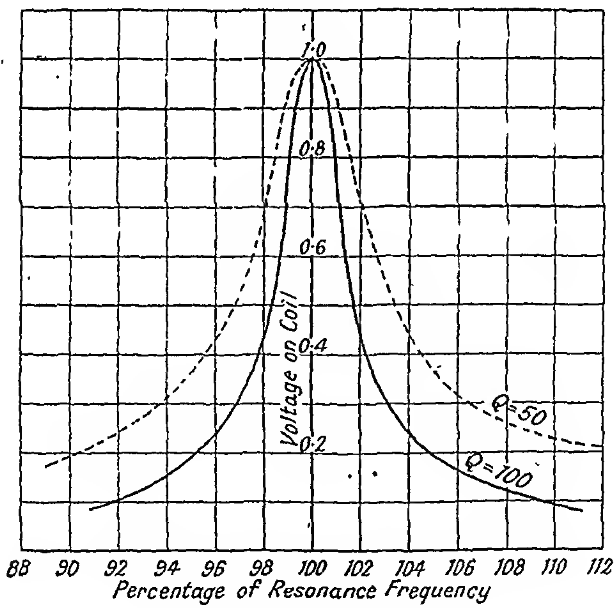


FIG. 78.—RESONANCE CURVES.

a large inductance; for the coil has lower impedance (reactance) than the condenser, the coil current is bigger and so there is a net lagging or coil current in the common lead. This means L and C can be replaced by a large coil. The aerial forms a series condenser to it and so series resonance is present in effect with a magnification across the "coil" which is the circuit connected to the grid. The circuit also gets rid of unwanted stations because of the tuning.

The graphs for a plain series circuit are shown in Fig. 78.

The current is smaller with $Q = 50$, i.e. a larger resistance: the curve gives fractions of the peak value, calling the peak I.

Note also the flatter peak for the lower "Q."

CHAPTER XIV

THE VALVE

NO single invention has ever made such an advance in light current engineering as the valve. Indeed the big water-cooled valves used for Transmitters are no longer "light current" engineering except in the complexity of the circuits and principles used in connection with them.

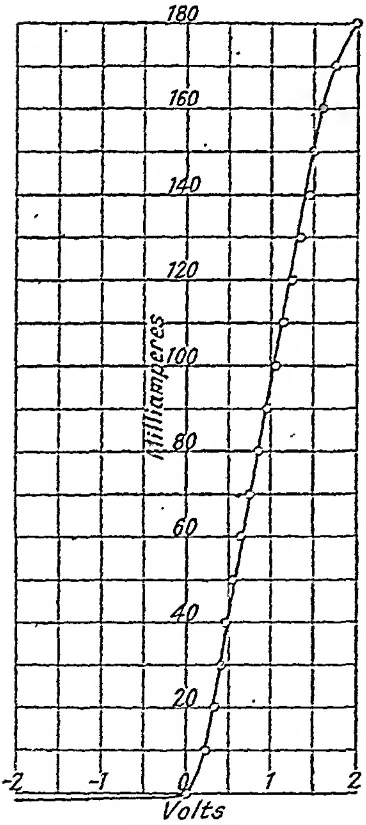


FIG. 79.—TEST ON A CRYSTAL.

The great thing about the valve is that a weak alternating voltage can be put on the grid, that is, between grid and filament and a stronger voltage, a copy if desired, can be obtained from the plate, between the plate and filament.

In the early days it was not only the weakness of the currents generated in the receiving aerial which made reception difficult, it was the fact that the currents were high frequency ones which would come over the ether in reasonable strength but would not work a telephone or any ordinary piece of apparatus. The first detector in common use was a crystal. It was called a detector because there were the currents, from say, Paris 400 miles away or more, but if they were flowing in the tuned receiving coil how

could one tell they were flowing? The crystal, tested with a battery allowed current to flow one way only, like a one-way street. With an alternating current the crystal allows half waves to flow.

See Fig. 79 for a graph of a test on a crystal. The series of half waves flowing through a crystal would operate a micro-ampmeter or headphone and so the presence of the current was detected. The valve was first designed as a detector. Edison, when making his electric lamps, had sealed a metal plate into the lamp quite distinct from the hot filament and found a current flowing in the conventional direction from cold plate to hot filament. (See Fig. 80).

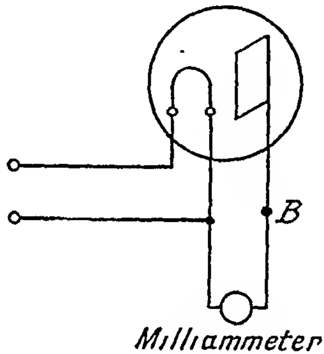


FIG. 80.—EDISON'S VALVE.
First designed as a detector by the Inventor.

The current according to convention flowed *to* the hot filament. This helped to prove the convention wrong; but we still keep it. It is like saying the sun rises in the east and sets in the west. It is accepted, though everyone understands that it is the earth which rotates from west to east.

Fleming used this for detecting radio waves because, although a little current flows with no battery in the plate circuit, a much larger current flowed if a battery was put in at *B* with positive connected to plate and negative to filament, but none flowed with the battery reversed. The valve was then a rectifier of alternating current when the *AC* was put in the ammeter circuit at *B* say.

This was called a diode valve. The *AC* might be a high frequency wave and the D.C. meter might be replaced by

phones if a musical or speech programme is being received. The hot filament emits electrons.

The Triode.

A great invention was made when the grid was added. This is a spiral of wire wrapped round, but not touching, the filament, and it is in between the plate and filament. It does not touch the plate, either. A high voltage or H.T. battery is put in series with the plate to help the electronic current to flow from filament to plate. If, now, a negative voltage is put between grid and filament the electrons are repelled from the grid and no current flows in the grid circuit, but the plate current is altered too. VARIATON in the grid voltage affects the plate current, as shown in Fig. 81, which shows typical curves for a triode valve. Each curve is plotted with one fixed value of H.T. voltage. The uses of the valve are bound up in these curves.

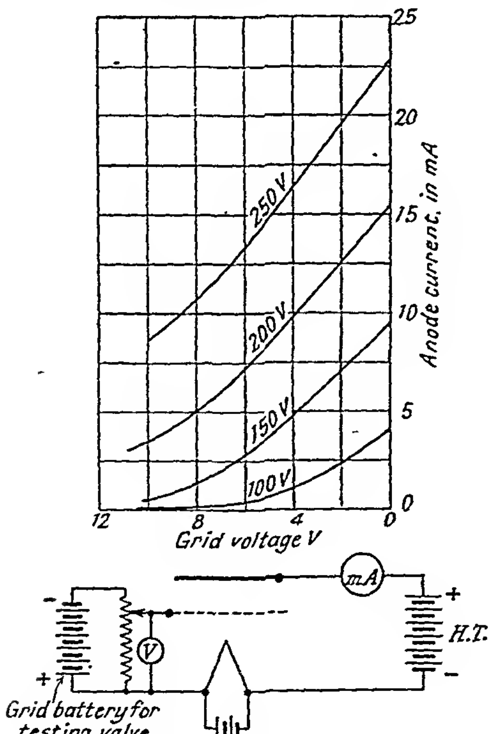


FIG. 81.—CURVES FOR TRIODE VALVE.

Constants of Triodes.

Notice that change of grid voltage from, say, 0 to 4 volts lowers the plate current by about 5 m. amps.

wherever we go on the straight parts of the characteristics. This means that 1 volt changes the plate current by 1·2 ma. This is called the MUTUAL CONDUCTANCE of the valve and g is the usual symbol for it. In this case $g = 1{\cdot}2$ milliamps. per volt.

Notice now that a reduction of 50 volts in plate voltage is needed to give a reduction of the same 5 ma in the plate circuit and vice versa, which means that as regards changes of plate voltage it takes 50 volts to give 5 ma change; so the plate circuit acts like a 10,000-ohm resistance. This figure, a small change of voltage at the plate called dv divided by a small change of plate current dI is known as the PLATE IMPEDANCE, or resistance of the anode, Ra. That is $Ra = \frac{dv}{dI}$

Last of all note that if the plate current changes by 1·2 m. amps. for 1 volt grid change, when the plate pressure is steady, the change of plate pressure to cause a 1·2 m. amp. change of plate current is $\frac{1{\cdot}2}{1000} \times 10{,}000 = 12$ since $V = RaI$ and Ra is 10,000 ohms. Hence 1 volt change on the grid does the same to the plate current as 12 volts change in plate battery voltage. Now it is seen why a valve amplifies; the figure 12 which is always g times Ra is called the AMPLIFICATION FACTOR. The symbol is μ, the Greek mu.

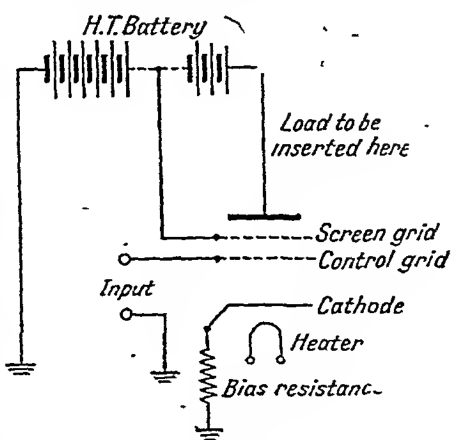


FIG. 82.—TETRODE SCREEN GRID VALVE.

Since the curves for the valve are a series of parallel and equally spaced straight lines, any change of plate current caused by a combined alteration in GRID VOLTAGE *and* PLATE VOLTAGE can be predicted by

finding the effect of the two factors separately. The triode valve is an excellent amplifier of music, but at high frequencies it is apt to generate extra oscillations when one is trying to amplify the weak incoming waves. This is due to capacity between grid and plate.

The screen grid valve or tetrode overcomes this. It has an extra grid between the control grid and the plate. (See Fig. 82).

The screen is connected to a tapping on the *H.T.* battery and now the plate current at full plate voltage does not alter much when the plate pressure is changed. This makes the plate impedance $Ra = \frac{dv}{dI}$ very high. It may be as much as several million ohms. The value of "*g*" the milliamps. plate current change per volt change on the control grid, is about the same as for a triode of the same type. The curves for different plate voltages come near together as in Fig. 83 because of the high *Ra*.

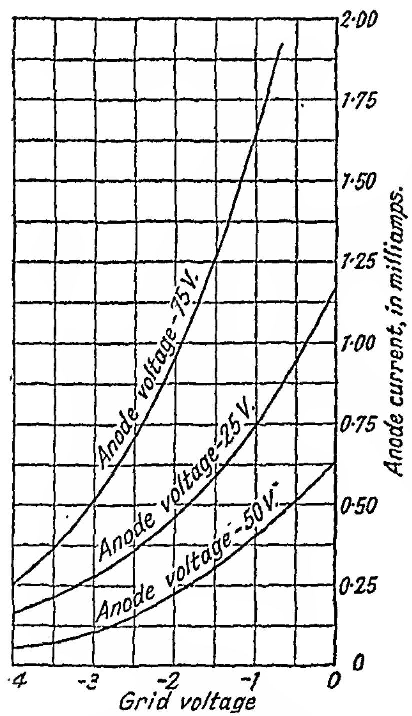


FIG. 83.—TETRODE CURVES.

There is one peculiarity, however. In a triode, the curve for 150^V plate is below that for 200^V plate and so on. In the tetrode they are not in order and the reason is explained from Fig. 84 which shows a different way of plotting valve characteristic curves. The grid voltage is fixed to get each curve, and Plate Current is

plotted against Plate Voltage. There is a kink in the curve at a certain voltage in the case of the tetrode and it occurs when the plate pressure is somewhat below the screen voltage. The kink or fall in plate current is accompanied by a rise in screen current. The explanation is that when an electron from the filament hits the plate it may knock out several electrons from the metal. This is called *Secondary Emission.* When the plate voltage is well above that of the screen the electrons return to the plate and there is a normal plate current. If, however, the screen is at a higher voltage, the emitted electrons go to the screen and increase the screen current. A very low plate voltage gives no secondary emission because the bombardment of the plate is not great enough.

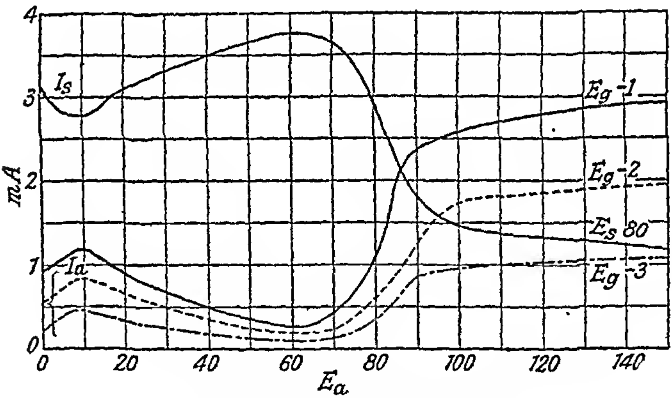


FIG. 84.—TETRODE CURVES.
Anode Current *Ia*, Anode Voltage *Eg*, *Is* is the Screen Current, *Es* is the Voltage.

The Pentode.

In the pentode an extra grid at the cathode potential is put between the screen or high voltage grid and the plate, to prevent secondary emission. It repels and so returns electrons to the plate, with the result that the kinks are taken out of the curves. (See Fig. 85).

This way of drawing characteristics is now common, but

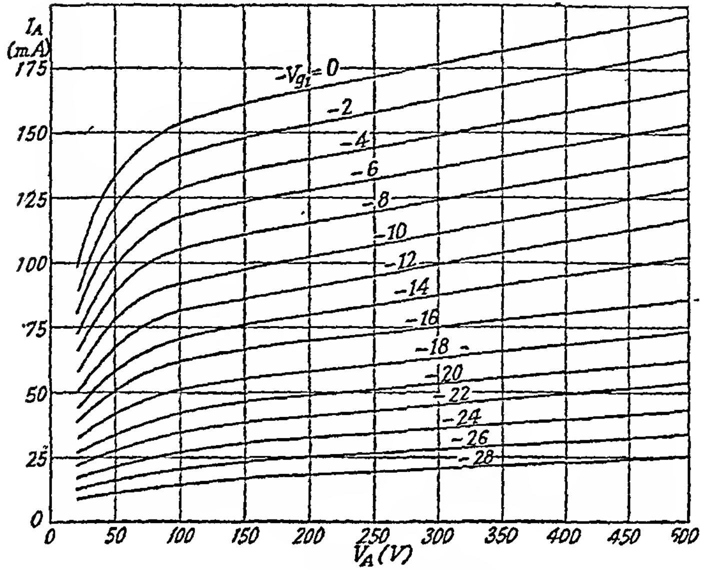


FIG. 85—PENTODE CURVES.

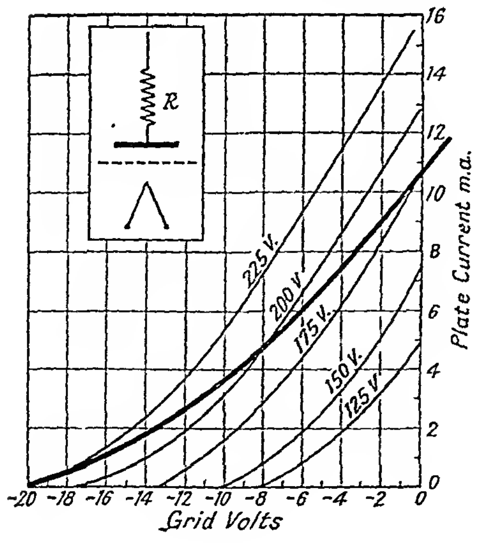


FIG. 85A. DYNAMIC CHARACTERISTIC OF A VALVE.

all the information which can be obtained from this type of characteristic can be obtained from the $V_G—I_P$ curves for the valve. What is often wanted is the characteristic curve for a valve with a load in the plate circuit. (See Fig. 85A). R is the load. Suppose the curves for the valve alone are as shown, and an external resistance R is put in the plate circuit, of value 5,000 ohms. The plate supply voltage is 250 in this example. When the current in the plate circuit of the valve and in the resistance is big, there is a big drop across the resistance and a low voltage on the plate. A *small* plate *current* means little *drop* and a big voltage on the plate itself, an important point.

Assume values for plate current and calculate voltage drops in the 5,000-ohm resistance thus:

I.M.A.	*Volts Drop in Resistance.*	*Actual Plate Voltage.*
0	0	250
5	25	225
10	50	200
15	75	175
20	100	150

Now find points on the set of curves for the currents and plate voltages in the table. Join these up and the result is what is called the *dynamic characteristic.*

Its straightness or otherwise, shows whether there will be much distortion, i.e. whether the plate current will be a faithful copy of the input voltage applied to the grid.

To Find the Power Output.

Suppose the variations of plate current as seen on the dynamic characteristic are from 5 to 13 ma in a 5,000-ohm load. The peak to peak current swing is $13 - 5 = 8$ ma and half this, 4, is the current peak value. The *RMS* values

are less than peak values, the factor being $\sqrt{2}$, so current of $\frac{4}{\sqrt{2}}$ *ma* making RI^2 to be:

$$\text{Watts} = \frac{5000 \times 16}{2 \times 1000000} = {\cdot}04 \text{ watts.}$$

One can draw a curve on the set of characteristics, for the maximum anode dissipation, above which the plate will get too hot, provided one has the makers' figure in watts for the safe limit. If it is 10 watts the voltages and currents are not to exceed such figures as:

Current *ma*	*Voltage*
50	200
100	100
120	83

This is the voltage actually on the plate when that current is flowing; not the voltage across the load resistance or impedance as well.

Direct and Indirectly Heated Valves.

In the early valves, and in the modern battery valve too, the hot filament emits the electrons. For operation on A.C. mains a type of valve has been developed in which the hot wire is bent into a hairpin and pushed into a "Cathode tube" which is insulated from it. It warms up the tube as hot water does a pipe, and the outside is painted with the chemicals which give off the electrons. This makes possible a novel type of bias arrangement. (See Fig 86).

Suppose it is desired to give -4^V bias and the valve has a plate current of 8 ma with this bias, these figures coming from a catalogue or from curves.

When the current flows through the bias resistance R, the cathode is positive above earth because of the RI drop.

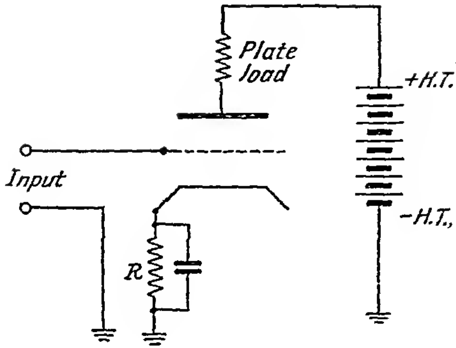


FIG. 86.—BIAS CIRCUIT.

The grid is connected through the transformer or through a high resistance to earth and so is negative to the cathode. In this example $4 = R \times \frac{8}{1000}$ or $R = 500^{\omega}$. Since increase of plate current (always caused by *positive* grid swing in the usual way) increases the bias with this system, making the grid go a little more *negative*, there is loss of amplification. A $50\mu f$ electrolytic condenser across R usually cures this. It need only be rated for the bias voltage.

CHAPTER XV

OSCILLATORS

The Triode Oscillator.

THE triode valve can be made to generate sine wave currents. Such a circuit is called an oscillator.

The simplest oscillator is perhaps the Meissner. (See Fig. 87). This oscillator has one condenser and two coils. The two coils are arranged so that some flux from the plate coil cuts the turns of the grid coil. The *M* represents that there is a mutual inductance of *M* henries between the two coils. The fundamental rule for oscillation is this:

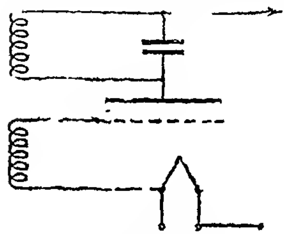


FIG. 87.
MEISSNER OSCILLATOR
MUTUAL INDUCTANCE OF COILS = M.

Rule for Oscillation.

If a slight positive pressure on the plate (i.e. an increase of voltage at the plate itself) causes a sufficient negative pressure on the grid, then there will be oscillation.

Expressed in figures it means this: When the plate goes more *positive*, the external circuit *must* make the grid more *negative*, and when the plate goes in a negative direction, say, from + 100 volts down to + 90 volts the grid *must* go more positive, i.e. from, say, -6^{V} grid bias to -5^{V} grid bias.

This is simply because a valve with a load in the plate circuit works this way. *Negative* movement of the grid means *reduced* plate current and a plate voltage which is nearer to the + end of the plate battery, because of less drop across the load with the smaller current according to Ohm's Law.

If the plate coil is the wrong way round with respect to the grid coil, one of them must have its ends reversed. If the two are wound on the same former, the end leading to the grid must go the opposite way round the former to that end of the other coil which goes to the plate; then the plate will go positive for grid negative, and the valve can oscillate.

The Calculation for this oscillator consists in assuming a voltage of, say, one volt maximum value (or else R.M.S. value instead) on the grid. The effect is followed by the j notation from the plate to the plate coil and right through back to the grid.

See Chapter XXX for the j notation.

The current in the plate coil affects the grid coil, and the voltage on the grid must be the 1 volt with which the calculation began, for there cannot be *two* values of voltage on the grid any more than a man can be five feet high and, also, six feet.

This produces an equation: by equating the calculated voltage on the grid coil to the 1 volt assumed to begin with. The equation breaks up, in the manner shown in the chapter on the j notation, to form two equations. One gives the condition for oscillation, showing that M must be big enough to give the required voltage assumed, and the other gives the frequency of oscillation as

$$f = \frac{1}{2\pi} \sqrt{\frac{1}{LC}\left\{1 + \frac{R}{R_a}\right\}}$$

where R_a is the internal plate impedance of the valve. This equation clearly shows that the frequency generated is not the simple $w = \frac{1}{\sqrt{LC}}$ of the circuit, in resonance to forced vibrations, but depends on the coil resistance R, which includes some losses, and on the plate impedance. If this is altered by, say, a change of H.T. voltage the frequency will alter too.

A very simple way to understand the operation of the circuit is to consider that as the tuned plate circuit is nearly at resonance, one need study the currents and voltages in this circuit alone. This is true, because the grid voltage is a copy of the back voltage generated in the self inductance of the plate coil, so long as no grid current flows.

A considerable current flows or circulates backwards and forwards round the tuned circuit like the to and fro movement of a watch balance wheel. Meanwhile the voltage across the tuned circuit is rising and falling, and reversing regularly, being greatest when the current is just about to reverse. One neglects the average or steady value of plate current for

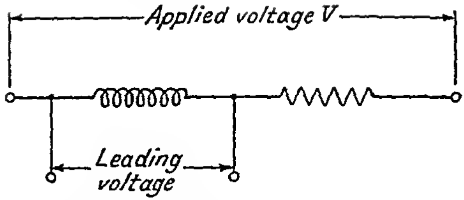


FIG. 91.—PHASES IN THE MEISSNER OSCILLATOR.
As regards the coil and its resistance.

Applying the same ideas as in Fig. 90, but in this case to the inductance and resistance of the plate coil we see that the voltage spent in the inductance of the coil leads on the total voltage V as in Fig. 91.

This voltage may, and in practice does come into phase with the voltage μ because the voltage on the inductance L which we have called x causes a voltage of similar but opposite phase in the grid coil and this is the 1 volt we started from. On the other hand, the following is important.

Limit of Swing of Oscillation.

On the assumption that the valve is linear, i.e. $\frac{1}{2}$ a volt on the grid causing $\frac{\mu}{2}$ volts on the plate and so on, there is nothing in the mathematics to show what the size or amplitude of oscillation will be. The valve curve is never really straight, and oscillation builds up until the valve is used with the grid swinging so far that the bend of the characteristic is encroached upon, with resulting reduction of μ at that point, and so of average μ throughout the cycle.

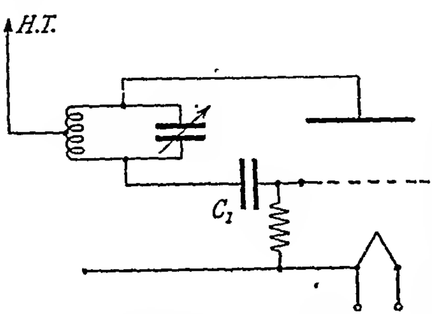


FIG. 92.—THE HARTLEY OSCILLATOR.

Further, if grid current flows, and it actually does, when automatic bias of the type used in Fig. 92 is used (and more so when it is not used) then a bigger oscillation means more grid current out of all proportion, since the grid

current is a parabolic curve, and the result is to reduce the voltage across the grid coil, and so a limit of swing is reached.

Where M is made very big the type of oscillation is not controlled so much by the LC value of the tuned circuit, and may be of much lower frequency and bad wave shape.

The Hartley Oscillator (with Automatic Bias).

This type of oscillator has one coil, with a tapping, as shown in Fig. 92. The tuning condenser tunes the whole coil. The condenser C keeps H.T. off the valve grid but it does more. Grid current flows when oscillation begins, and this changes the tiny condenser C_1. The voltage reached depends on the resistance R which gives the grid a definite voltage of bias. R is a leak on the condenser through the H.T. battery and plate coil. The condenser charges in such a way (neglecting the steady H.T. on it) as to make the grid negative, and so apply a bias; the bias in turn makes the grid current far less than in the case of an oscillator with no bias, thereby reducing losses, and also acts as a limiting device to the oscillation amplitude as it drives the grid to a less steep part of the valve characteristic than that near the region $V_G = 0$.

Here it can readily be seen that the plate goes negative when the grid goes positive according to our rule, because the grid and plate are at opposite ends of the tuned circuit, which is tied down in the middle only, to the positive H.T. battery terminal of fixed, if high, voltage. This is like the fulcrum of a see-saw.

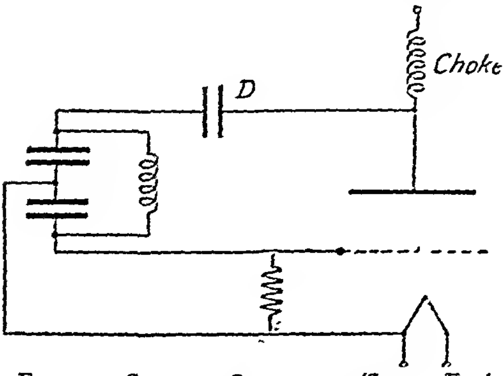


FIG. 93.—COLPITTS OSCILLATOR (SHUNT FED).

Fig. 93 shows the wiring diagram of the Colpitts Oscillator.

Often the above two oscillators are what is called "shunt fed."

Here again the see-saw idea is seen in opera-

tion. The advantage of this oscillator is that, in a set with a wave change switch, there is only one coil to change, and it has no tapping.

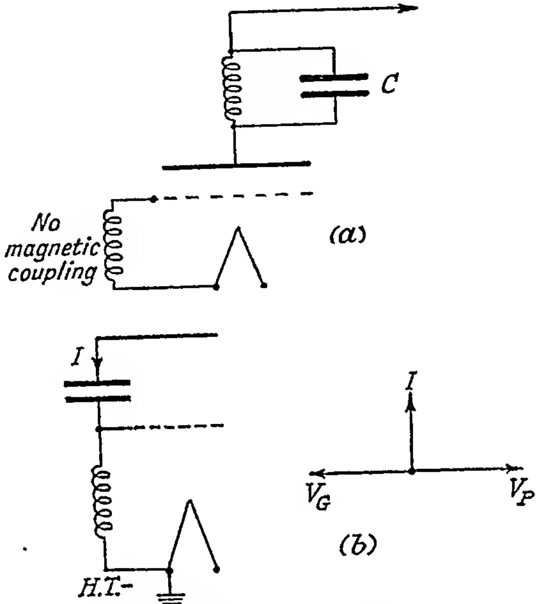


FIG. 94. OSCILLATOR ELECTRODE CAPACITY COUPLING UNTUNED GRID, TUNED PLATE.

Before the invention of the tetrode, triodes oscillated only too freely when both the plate and grid circuits were tuned, and this was caused by the capacity inside the valve, between plate and grid. A popular oscillator used by amateurs is shown in Fig. 94 (*a*) and its explanatory diagram is shown in Fig. 94 (*b*), with the vector diagram. It is not a Meissner as the coils are not coupled. Often a Meissner at some small condenser setting oscillates wonderfully well. It is probably, almost certainly, oscillating in this way when it does that.

The large grid coil is not coupled to the plate coil as in the Meissner oscillator. The explanation to the circuit is that the interelectrode capacity gives a series circuit as in Fig.

94 (*b*). If now the plate circuit is about in tune, and if the grid coil impedance is large, and yet much smaller than the reactance of the plate to grid capacity, then as regards the alternating plate voltage Vp there is a leading current I flowing to the filament through the coil as shown in the vector diagram Fig. 94 (*b*).

In the grid coil, however, the voltage leads the current I by 90° as usual. Thus the grid and plate voltages are in anti-phase, which is our criterion for oscillation.

Tuned Grid-Tuned Plate Oscillator.

The tuned grid tuned plate oscillator, Fig. 95, works on this principle and keeps its frequency more constant and less affected by valve characteristic changes than other oscillators mentioned previously. Often a crystal with a sharp mechanical and electrical resonance frequency characteristic is built into an oscillator circuit to stabilise the frequency.

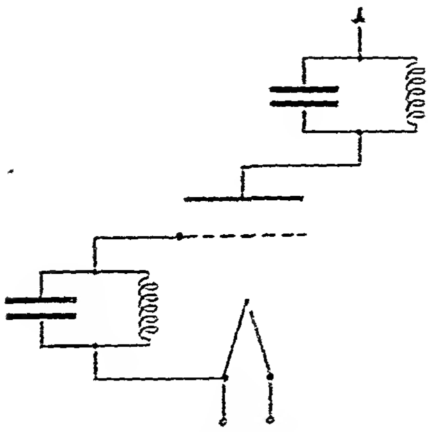


FIG. 95.—TUNED GRID-TUNED PLATE OSCILLATOR.

Oscillators with automatic Bias obtained from a condenser and grid leak are often designed to work with a very large bias. This is known as "Class C" working and is described under amplification.

CHAPTER XVI

MODULATION

THE action of modulating a high frequency carrier wave is to make its amplitude larger and smaller in such a way that the tops of the waves give a picture of the speech wave. (See Fig. 96).

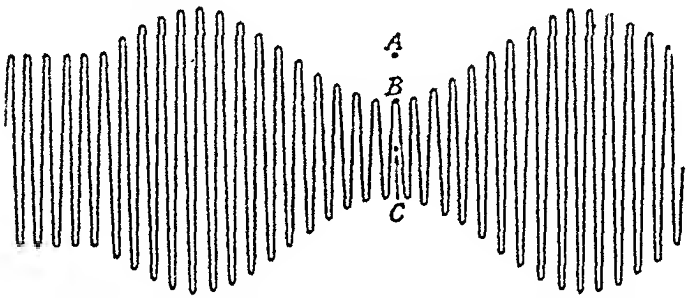
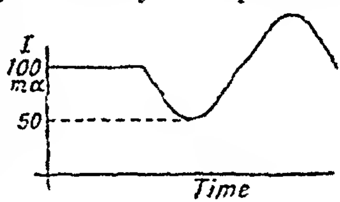


FIG. 96.—MODULATION OF HIGH FREQUENCY CARRIER WAVE.

The wave crosses the zero just as many times per second after modulation as before, but the heights vary. The ratio $\frac{AB}{AC}$ is called the depth of modulation. If $AB = BC$ it is $\frac{1}{2}$ or 50 per cent. Thirty per cent modulation means AB is ·3 of AC.

The simplest way to study modulation is to compare it with the effect of speaking into a carbon microphone, as regards the effect on the direct current through the microphone. Suppose in a given case the microphone resistance doubles, and cuts



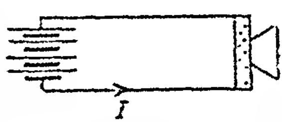


FIG. 97.—A MODULATED CURRENT. The Current in a Microphone circuit is here shown as an example of modulation.

the current to half its steady value, which we may take as 100 ma. (Fig. 30). Then M is $\frac{1}{2}$.

If now the battery voltage were reduced to half its strength the steady current would be 50 ma falling to 25 ma when the microphone resistance doubled. Thus the A.C. component of current *added* to the original by the mere act of speaking into the microphone is 50 ma maximum, i.e. $\frac{50}{1000}$ Sin ωt amps. with full battery but only 25 *ma* maximum with half the battery strength or half the STEADY current.

Thus the added A.C. is a given fraction of the steady D.C. for a given loudness of speaking. Thus the *added* A.C. is a sine wave (or else some other wave) *multiplied* by the steady current.

It is (STEADY VALUE) TIMES (M SIN ωt).

The Sin wt may be Cos ωt. That is a detail. The ω is for the speech and is $2\pi f$.

The total current is then

STEADY + (STEADY) (M SIN ωt) or

STEADY $\{1 + M \text{ Sin } \omega t\}$.

Now apply this to modulation of a carrier. The ω for the carrier may be distinguished from that for the speech by calling it $\omega_0 = 2\pi f_0$ and calling the speech $\omega_s = 2\pi f_s$, f_s and f_0 being speech and carrier frequency respectively.

Substituting a steady high frequency carrier for the steady D.C. in the telephone, one gets $V \text{ Sin } \omega_0 t \ \{1 + M \text{ Sin } \omega_s t\}$ for the modulated carrier expressed mathematically. This is quite a valid expression; because at one time the carrier currents to the aerial were put through the microphone, so it is quite right to replace the D.C. with sin $\omega_0 t$.

The $1 + M$ Sin $\omega_s t$ goes down to $1 - M$ when Sin $\omega_s t$ reaches -1, which is when $\omega_s t$ comes to be an angle of 270° and it goes up to $1 + M$ when Sin $\omega_s t$ reaches $+1$ at a peak of the speech wave when $\omega_s t = 90^\circ$ or more correctly $\frac{\pi}{2}$ radians.

If we subtract the original unmodulated carrier we have

$$MV \text{ Sin } \omega_0 t \text{ Sin } \omega_s t$$

which is a rapidly reversing "beat" tone. The frequency of

the vibration is the carrier frequency, say a million a second, but the "beat" frequency is just double the speech frequency, for there is a pair of beats for each cycle of the slower speech wave.

Further, as Sin $\omega_s t$ goes alternately positive and negative, and multiplies the carrier Sin $\omega_s t$, every alternate loop of the beat has the carrier waves reversed in phase as is the case with beat waves.

The beat wave

$$MV \text{ Sin } \omega_0 t \text{ Sin } \omega_s t$$

may be expressed as

$$MV \tfrac{1}{2} \text{ Cos } (\omega_0 t - \omega_s t) - \tfrac{1}{2} \text{ Cos } (\omega_0 t + \omega_s t)$$

by using a formula in easy trigonometry. Now bracket t out:

$$MV \tfrac{1}{2} \text{ Cos } (\omega_0 - \omega_s)t - \tfrac{1}{2} \text{ Cos } (\omega_0 + \omega_s)t.$$

This means TWO SEPARATE WAVES OF STEADY AMPLITUDE; one of frequency $f_o + f_s$, i.e. carrier plus speech frequency, and another of $f_o - f_s$ or carrier minus speech frequency. These are called the upper and lower side band frequencies.

Note that the higher the speech frequency the further away from the carrier the side band frequencies are.

In a speech wave there are frequencies which lie anywhere between 200 c/s or less, and 2,500 c/s or more. Thus there are two side bands of frequencies, all high frequencies, that is, lying in the regions above and below the carrier as in Fig. 98.

The formula referred to is:

$$\text{Cos } (A - B) - \text{Cos } (A + B) = 2 \text{ Sin } A \text{ Sin } B.$$

Fig. 98 shows a carrier of 100,000 cycles per second, making the side bands stretch from 97,500 to 99,800 the lower, and the upper from 100,200 to 102,500 c/s.

For music the frequencies are at least up to 5,000 c/s which makes the side bands extend to 5,000 c/s on each side of the carrier. This is why broadcast transmitters have their wavelengths spaced about 10 kilocycles apart—to allow for 5,000 c/s above that transmitter with the lower carrier frequency and also 5,000 c/s below the other transmitter with the higher carrier frequency. In other words, the two side bands should not overlap when two stations are close together in their carriers. One may regard a modulated wave, then, as a jumble of frequencies round about the carrier frequency. The picture of a high frequency wave modulated with a single

sine wave tone, shown above, may be thought to have little practical value but its value is great. One may test a receiver with a carrier modulated by say 200 c/s then test again with 400 c/s modulating the same carrier and so on. The result shows how the whole receiver will act at each tone frequency by itself and so how it will act when all tones are present in music.

If the tests with 2,000 c/s and over are a failure, the higher tones of music and those consonants of speech like *t*, *d* and *s* which contain high frequencies will not be heard very well. Thus the carrier modulated by a single pure sine wave tone

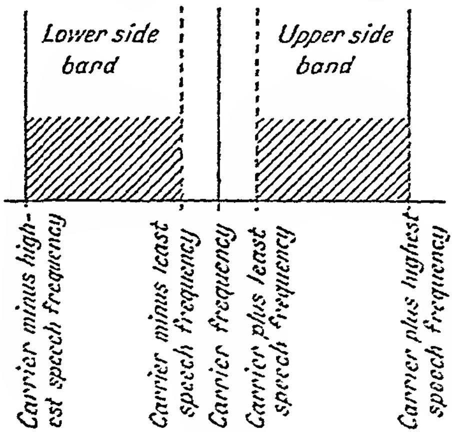


FIG. 98.—THE SIDE BANDS OF A MODULATED WAVE.

bears the relation of a spade to a garden when the performance of the set is considered. The spade will not turn the whole garden over at once; but used again and again, will do so.

The modulated wave, then, has no currents of speech frequency (called Low Frequency or L.F. currents) in it, but it carries the music by virtue of its *shape* just as the wood of a fretwork motto carries the message by virtue of its shape.

Further, the use of a carrier allows of tuning; and so of many stations operating all together at the same time, with different programmes; which could not be done if all the music went out on the ether in the form of musical currents.

PULSE-TIME MODULATION

This is a new way of modulating a "carrier." It consists of varying the timing of impulse trains of the high frequency wave. The wave is of constant amplitude which distinguishes it from amplitude modulation. It is of constant frequency which distinguishes it from frequency modulation.

The pulse frequency may be quite high. This means that a large band width may be required but in short wave work with the enormous frequencies which go with short waves, a large band width is readily available. This is different from medium wave broadcasting where the ether is very crowded and a conference has to determine the exact frequencies used, and where the 10 or 20 kilocycles band width needed for reproduction of music is hard to find.

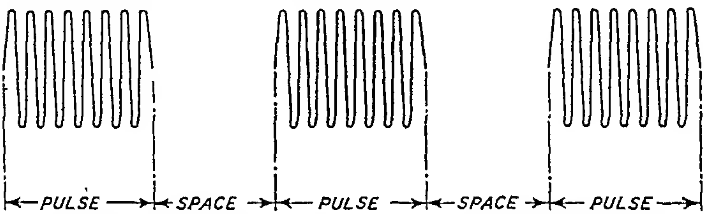


FIG. 99.—PULSE-TIME MODULATION. DURING MODULATION THE SPACING CHANGES.

The Advantage of Pulse-time Modulation.

The great advantage is that a message made weak by distance may be repeated by simply starting and switching a "local" oscillator on and off.

The advantage of this new form of modulation for short waves is that short wave oscillators are difficult to modulate really well. In the centimetre waves for wave guides, amplitude modulation problems are serious. It is, however, easy to start and stop an oscillator, and this is all that is wanted in pulse-time modulation; you just vary the moment of starting and stopping a pulse. One description is that the pulse length is a constant time but the time of the break period between pulses varies with the modulation. The

time between pulses does not vary when the wave is unmodulated. When it is modulated, the spacing varies and the pulses are just like the particles of air in a sound wave. There is "condensation"; pulses closer together; and there is "rarefaction"; pulses opened out, i.e. bigger spaces. Fig. 99 shows the train of pulses of a wave unmodulated.

There is no reason why the length of the pulse should be constant, and the spacing varied by the modulation. The spacing could be constant and the pulse length varied. Fig. 100 shows a wave which it is desired to transmit and the way the pulses vary in their spacing.

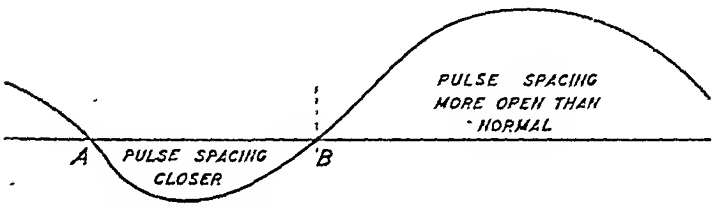


FIG. 100.—TRANSMISSION OF A MESSAGE BY PULSE-TIME MODULATION.

Detection of Pulse-Modulated Waves.

The number of microamperes of a detected wave naturally varies if the spacing is varied; so it is only necessary to detect in the ordinary way as for amplitude modulation.

Multi-Channel Work.

Several conversations can be carried on over one line by dealing the pulses out in the way that a pack of cards is dealt out to several players. The "cards" are modulated *after* being dealt out.

CHAPTER XVII

MODULATION CIRCUITS

THE three chief circuits for modulating a carrier with a low frequency wave are:

(1) Anode bend modulation (often called grid modulation);
(2) Choke Modulation.
(3) Octode Modulation.

These will be considered in order and are shown in Figs. 101–104.

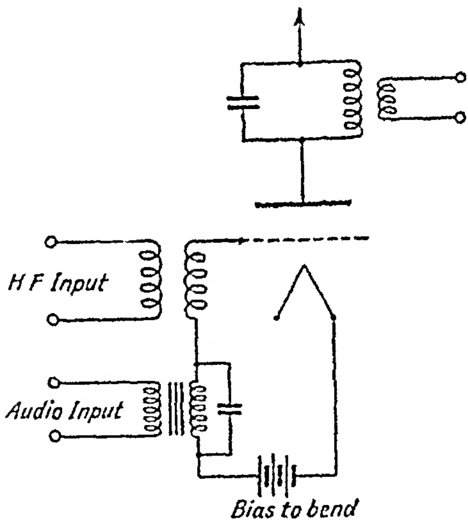


FIG 101.—ANODE BEND MODULATION.

Anode Bend Modulation.

The valve is worked on the bend of the grid volt plate current curve. The anode demodulator works by the difference between the slope after and before the bend. This circuit works by the change of slope on the bend being a constant change of slope per grid volt. A parabola does this.

Consider a carrier of small volume and an audio wave of

larger volume. These are added together by putting the transformer secondaries in series (Series connection always means addition) and applying the addition wave to the grid. The low frequency wave may be regarded as drifting the operating point to places on the characteristic with a greater or less slope, thus giving a "variable μ effect" as it is called when the same sort of technique is used for automatic volume control in a receiver.

Concentrate now on plate current.

The resulting plate current is *not* a copy of what was applied to the grid. The L.F. wave appears, distorted, with a carrier ripple; but the ripple is *more pronounced* in certain places.

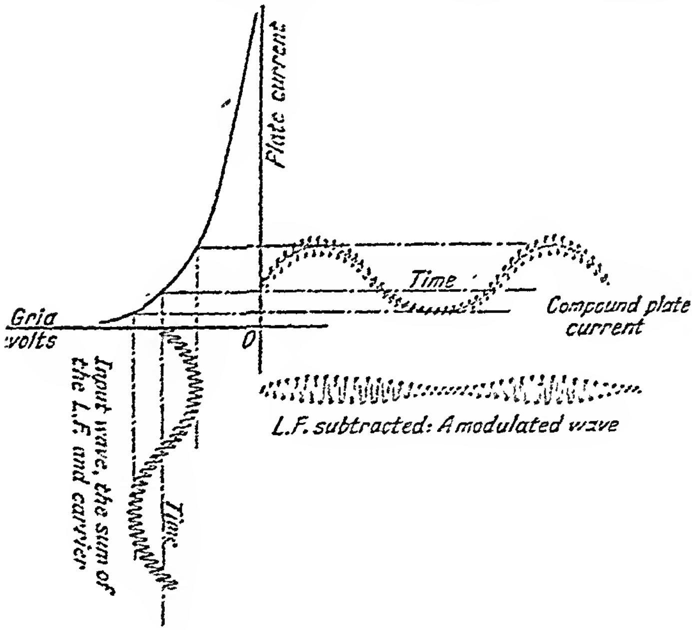


FIG. 102—SHOWING THE DISTORTION OF L. F. WAVE WITH PRODUCTION OF PRONOUNCED RIPPLE.

When the carrier frequency current in the plate circuit is separated from the L.F. wave (which is like coke in a gas works, only not useful) the carrier is found to be modulated,

which is just what is wanted. The drawing in Fig. 102 shows what happens.

The carrier need not be small in comparison with the L.F. A parabolic curve gives a term which is a correct product moment by moment of the two waves. Metal rectifiers having a similar curve will work. Grid bias of the cathode resistance type cannot be used since there is little plate current at the bend.

Choke Modulation.

This circuit works on a totally different principle. It is an experimental fact that with a correctly adjusted oscillator, the amplitude of oscillation depends on the length of the valve

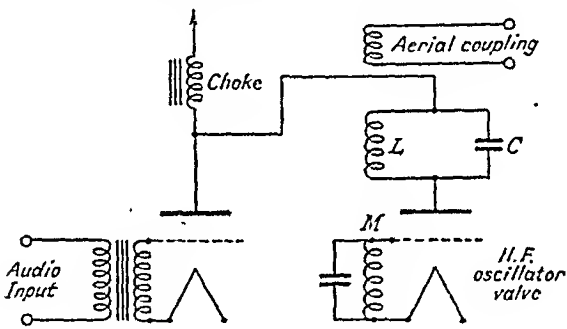


FIG. 103.—CHOKE MODULATION CIRCUIT.

characteristic between V_0O and the bottom bend. This length is settled by the voltage applied to the plate as in Fig. 81.

When the H.T. is supplied as shown in Fig. 102, it naturally varies with the speech wave applied to the grid of the modulator valve. The result is that the oscillator grid and plate current swing, and so the volume of carrier output, varies with the speech wave.

What makes an oscillator swing to an amplitude settled by the LENGTH of the straight part of the valve characteristic is that it builds up until the losses due to grid current when it swings positively set a limit there, and the reduced slope when it swings the other way provide a limit at that end of the line, too.

Octode Modulation.

The octode is only one type of valve with two "working" grids in addition to screens, etc. The electrons come up to the second working grid with its negative bias, and collect in a cloud known as a "virtual cathode". The size of this cloud varies when a signal is put on the first or inner grid. The size of the cloud or virtual cathode determines the "g", as it were, of the triode formed by the cloud, the second grid and anode. Thus the wave of plate current caused by the *RF* voltage applied to the 1st working grid is made larger and smaller in size by a wave applied to the 4th grid. (See Fig. 104). The speech wave may be put on Grid 4, which is the second working grid in an octode.

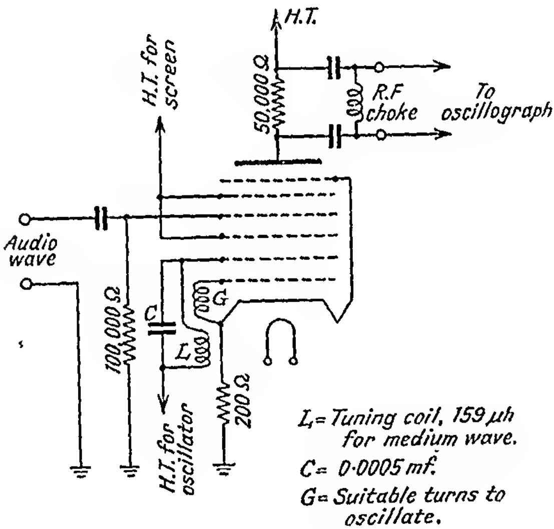


FIG. 104.—OCTODE MODULATION.

Thus the two waves are correctly multiplied together, which is modulation. There are other products of modulation as in all three modulation circuits, and the wanted one, the modulated carrier, is selected by tuned circuits (or filters) in the plate of the valve.

CHAPTER XVIII

DETECTION AND DETECTOR CIRCUITS

SEEING that high frequencies only affect the ether in such a way as to induce an appreciable voltage in a distant aerial, these high frequencies can be used for transmitting without any connecting wires. Since, however, these high frequency currents do not affect a telephone because it cannot vibrate so fast, and also because the ear cannot hear frequencies above about 15,000 at all (the range of sound frequencies is from about 60–8,000 c/s), it is necessary to make the modulated carrier somehow give a current of the musical frequencies which it carries.

This is easy to do graphically, one must rub out the bottom halves of all the high frequency waves. Taking a modulated carrier, when the bottom or negative half is removed by a "one way" circuit the rest is shown in Fig. 105. This drawing is a series of current pulses in one direction only.

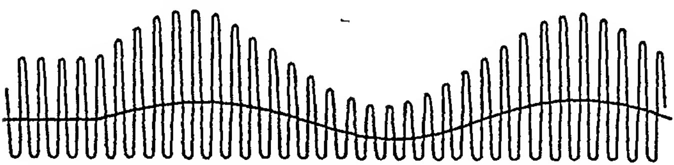


FIG. 105—ONE-DIRECTION CURRENT PULSES PRODUCED BY MODULATOR CARRIER.

Now average these and the result is a graph of the modulating or musical wave which modulated the carrier in the first place.

It does not seem obvious that this wave is a faithful, though reduced, copy of the modulating tone, i.e. of the shape of the edge of the carrier, but it is, because the carrier frequency is so rapid in vibration frequency compared with the frequency of speech, that no drawing of practical size can show the separate waves of carrier to scale, on the same scale as the speech. On an oscillograph the carrier is simply a "blurr" of light when the oscillograph time base goes slow

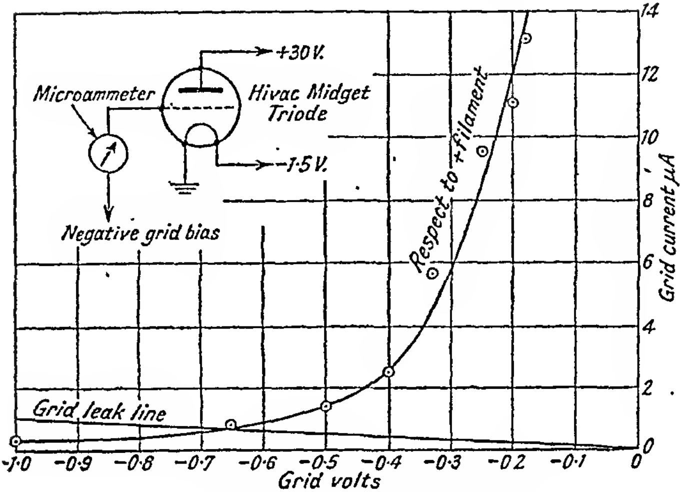


FIG. 107.—CURVE FOR A DIODE.

There are two detector circuits in common use as well as the plain diode detector circuit.

Leaky Grid Detector.

The circuit for this is shown in Fig. 108. The condenser *C* charges from the radio frequency currents, because of the curvature of the graph in Fig. 107. Fig. 109 is an enlarged portion of Fig. 107 showing that the two halves of the radio wave, though of equal voltage produce currents which are unequal as shown by the different heights of *AB* and *AC*. The condenser discharge circuit is shown in Fig. 109A and explained more fully later. (See Chapter XXXII).

The separate cycles of the radio wave put a charge on the condenser, and this charge is bigger, the greater the amplitude of the radio wave. Since the radio wave is varying in size with the modulation, the charge on the condenser varies with the modulation. This makes the condenser voltage a copy of the modulation. The condenser voltage is therefore the speech or musical voltage. The grid leak helps to discharge it during the "troughs" of the modulation.

that the two halves of the grid voltage wave are copied exactly to scale, but their slope being different the two scales are different for the plate currents. (Fig. 112.)

At all times and also, therefore, on an average, the lower half of the wave would be an exact fraction of the upper half, and so the subtraction would be an exact fraction of the total and taking an average as regards the high frequency currents in the plate circuit, perfect music would be obtained from a modulated wave.

A certain book published for the R.A.F. defines detection with a stroke of genius as being a form of distortion. In practice a sharp bend to a plate current—grid voltage curve gives anode bend rectification to a wave, if the valve has a bias to the bend; and further, seeing that all valves have a slight curvature

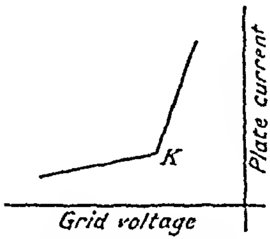


FIG. 111.—ANODE BEND DETECTOR CURVE.

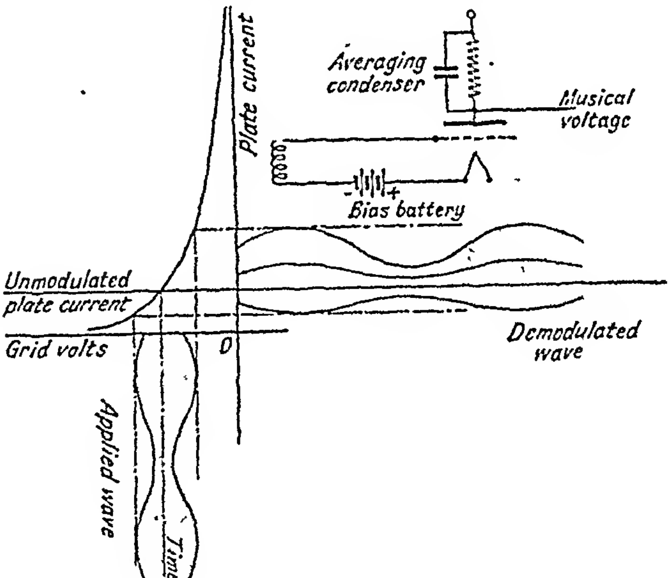


FIG. 112.—THE OPERATION OF THE ANODE BEND DETECTOR CIRCUIT.

of the characteristic, anode bend detection is always present to some degree.

With this form of detection the average plate current rises when the carrier wave is applied, in contrast with the case of the leaky grid detector, where it falls. This is of great interest in an understanding of the circuit, but is of no practical importance. In the ideal case where the negative half of the carrier is wiped out altogether—never realised in practice—the positive halves of the modulated wave only are left, as in Fig. 105.

Since an average of a loop of a sine wave is $\frac{2}{\pi}$ this would mean that a carrier of maximum strength 1 volt would become an average change in plate current of $\frac{g}{\pi}$ milliamps. with a mutual conductance g ma /volt and no plate load.

Octode Detection.

Since an octode gives a plate current which is, or contains a multiple term found by multiplying the two voltages applied to the two main control grids, one may put a modulated carrier from an aerial on one grid, and a local unmodulated oscillator on the other grid and get music at once if the oscillator is in step and in phase with the incoming carrier. This follows directly from Fourier's Theorem which says that two sine waves multiplied together give zero average value, unless they are of the same frequency.

The author has experimented in this direction and several receivers were built by him.

Dr. Tucker of the British Post Office also developed the scheme independently. His circuits appear in the technical press.

Reaction.

If a coil is put in series with the plate, and brought near to the grid coil, it induces high frequency voltages in the grid coil. These being a fairly faithful copy of the applied aerial voltage strengthen this, and give an increased carrier volume

applied to the grid, and so the result is much larger voltages and currents all round, with a good increase in the loudness of the music. This is called "Reaction". It is shown in the drawing given later of a complete receiver. If the reaction coil is brought too close to the grid coil the circuit, being that of a tuned grid oscillator, bursts into high frequency oscillation and generates a local high frequency wave. The frequency is usually a little different from that of the incoming carrier one is trying to receive, and the two heterodyne to produce a beat note. As the condenser is turned, the local oscillation alters in frequency and so the howl changes in pitch. This is the origin of the "whee-whee" heard in the headphones.

Notice that the signal causes a reduction in plate current with this circuit.

The leaky grid detector is postponed until later.

The treatment of it given in this work is thought to be original (see Chap. XXXII).

however, a resistance be put in the plate lead, the voltage across the resistance must vary, as current varies, according to Ohm's Law. Thus an alternating voltage will be developed across it by Ohm's Law. The alternating voltage may be measured separately from the steady D.C. drop caused by the steady plate current, by introducing a condenser at the plate. (See Fig. 114).

If the resistance carries an alternating current of 1 ma and the value of it in ohms is, say, 50,000, then the pressure output is 50 volts, but most voltmeters are quite useless for measuring it—even laboratory instruments. If it is of speech frequency the meter must be capable of working at

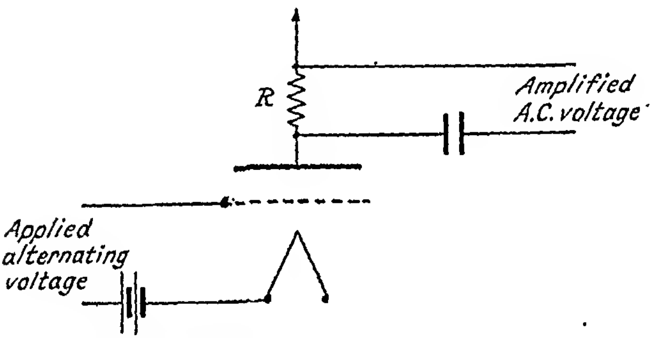


FIG. 114.—THE RESISTANCE CAPACITY CIRCUIT.

that frequency and it must be of very high impedance compared with the 50,000 ohms. A valve voltmeter of the type in which a small condenser is charged by diode action will do. An electrostatic meter is excellent if it is of a low reading type. A cathode ray oscillograph is good, too. Calibrate it by putting on a voltage from a mains A.C. plug which will give power to work any meter. (See Fig. 115.) See how big a wave one gets for, say, 50 volts or 25 volts or less.

Multi-stage Amplifiers.

One great advantage of the valve is that the output of any valve may be fed to another for further amplification. The problem which immediately occurs is, how should the valves

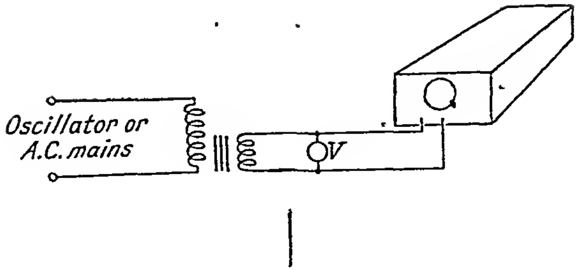


FIG. 115.—CALIBRATION OF OSCILLOGRAPH.

be coupled? The easiest way and about the best for musical or L.F. work is Resistance Capacity Coupling.

Resistance Capacity Coupling.

The circuit is shown in Fig. 116.

The impedance of the condenser to the lowest musical frequency (for which $\frac{1}{C\omega}$ is greatest) should be small enough to "T" on to the resistance R without making it appreciably larger. Also R_2 should be large compared with R so as not to "shunt" down R and reduce the alternating voltage. An increase in plate current due to the grid of the valve going less negative on one half wave of the signal voltage, will

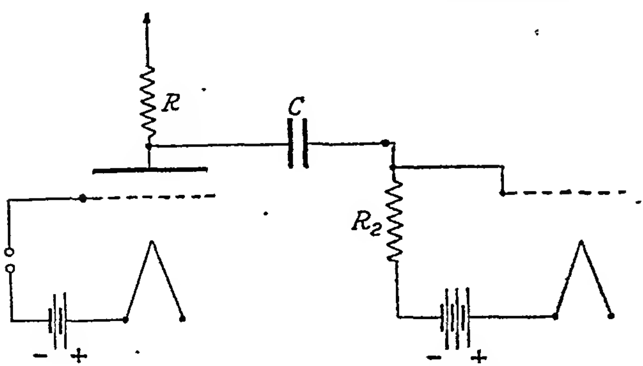


FIG. 116.—RESISTANCE CAPACITY COUPLING.

increase the drop across the resistance R by Ohm's Law, $V=RI$. The result is a lowered plate voltage measured *at the Plate*, i.e. an instantaneous voltage. This has an effect on the plate current, and so helps to decide the change of plate current which decides the change of plate voltage. Since the voltage of the H.T. battery is fixed, we may regard our amplified A.C. voltage as developed across R, that is between plate and the H.T. + terminal or else between the PLATE and the filament which is the negative H.T. terminal. The latter is a convenient way to think of it. The ratio of alternating voltage developed between plate and filament (or across R) to the voltage applied to the grid of the same valve is called the stage gain.

Apply 1 volt to the grid, and call the plate voltage change, x. Think of the 1 volt as an alteration of the grid bias, rather than alternating for the moment. The current in the valve would be "g" alteration if the plate voltage did not vary. There is an alteration of plate current caused by the variation x of plate voltage which is $\frac{x}{R_a}$ by the meaning of R_a the plate impedance. The nett change of plate current is then an increase g less a decrease of $\frac{x}{R_a}$ which is $g - \frac{x}{R_a}$ but the x is the drop across R, so by Ohm's Law again $V = RI$, so $x = R\left(g - \frac{x}{R_a}\right)$ which is $x + \frac{Rx}{R_a} = Rg$. Solve for x and $x = \frac{RR_a g}{R_a + R}$ but $R_a g$ is the μ of the valve by Ohm's Law so we have $x = \frac{\mu R}{R + R_a}$ for the stage gain.

Since the stage gain is the voltage across the resistance R the current in R is $\frac{\mu}{R + R_a}$ which is the current which a voltage μ would put through R and R_a in series. The valve therefore acts as though the application of 1 volt to the grid sets free μ volts inside the valve, even when there is an external load in the plate circuit.

It is sometimes asked why one cannot think of the stage

gain as the voltage drop in the R_a of the valve. This is not right, because there is the live voltage μ in the valve. The drop across R_a is not the sole internal voltage. Subtract $\frac{\mu R_a}{R + R_a}$ from μ and the stage gain is $\frac{\mu R}{R + R_a}$ as before.

Example 15. A valve with $\mu = 39$ is used with an external resistance of 20,000 ohms. It has a plate impedance of 10,000 ohms. What is the stage gain?

$$\frac{\mu R}{R + R_a} \text{ is } \frac{39 \times 20000}{20000 + 10000} = 26.$$

This means that an alteration of a volt in the grid bias would cause 26 volts alteration in plate voltage. If the grid is made 1 volt more NEGATIVE the plate is 26 volts more POSITIVE, and vice versa.

One volt R.M.S. alternating current on the grid causes 26 volts R.M.S. at the plate. One volt maximum value causes 26 volts maximum value. It is proportional as long as the curved portions of the characteristic are not encroached upon. Half a volt gives 13 volts and so on, if the Stage gain is 26.

Transformer Coupling.

The primary of the transformer ought to be of such a high impedance that LW is big enough even at low frequencies to make the full voltage V_G developed in the valve appear across the primary. For this, since LW is "Teed" on to R_a at right angles an LW of 3 times the plate impedance is enough. If one wishes to go down to 50 cycles with a 10,000-ohm valve, then LW should be 30,000 ohms at least. At 50ν this means about 100 henries. Then nearly μ volts will be developed on the primary for 1 volt on the grid. The secondary voltage is $n\mu$ if the turn ratio is n step up to the next valve.

Example 16. Find the Stage gain with the previous valve coupled by a 4 : 1 transformer of good design. Here $\mu n = 39 \times 4 = 156$.

Class B Amplification.

For audio work one must work on the straight part of the valve curve unless a push pull circuit is used, but it has been

found an advantage to let the grid go positive and obtain bigger plate currents. The previous valve must deliver grid current to the grid of the valve in question so the impedance looking back should not be too high. The previous valve is then a kind of power valve and is called a "driver".

Power Valves.

Valves are used to produce an amplified voltage to go to the grid of the next valve, but finally currents in—say—the low resistance speech coil of a loud speaker must be produced. In order to get big enough currents a larger size of valve is used which will give big variations of current. The plate impedance will be fairly low. Suppose it is 1,000 ohms. One now matches the speech coil which may be 6 ohms to the valve by a transformer. The turn ration here would be $n^2 = \frac{1000}{6}$ or $n^2 = 160$ making n about 13:1 step down.

Push Pull Circuits.

The greatest distortion caused by the curvature of the valve characteristics is found in the last valve. A push pull circuit is one using two valves as shown in Fig. 117. As the upper valve draws more plate current when its grid goes more positive, the lower valve draws less, because its grid then goes more negative. This is when the pressure in the input transformer acts "upwards".

The point is that, owing to the varying steepness of the

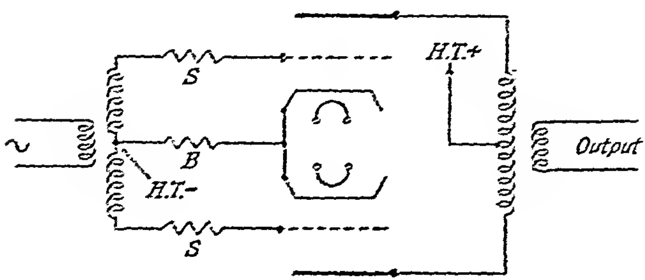


FIG. 117.—PUSH PULL AMPLIFICATION.

valve curve, the current in the upper valve increases more than the current in the other decreases. Like a tired and a fresh horse, they give a good result between them. The output is the sum of the "increase" and the "decrease". Next half cycle it is "decrease" for the top valve and "increase" for the lower one, and this half of the wave is amplified like the other half. If the characteristic curve is Current $= a + bx + cx^2$ when x is made negative for the second valve the result is $a - bx + cx^2$. These are subtracted as the turns on the output transformer go round opposite ways and we have nett magnetising effect $= 2bx$, which is proportional to x the grid voltage. The cx^2 goes out showing no $\sin^2 x$ which means no second harmonic in the output, which *would* arise from the curve of one valve only. Also the steady plate currents do not saturate the core of the transformer. They cancel. The grid bias is caused by the resistance B which need have no condenser across it. The resistances S, S, in the grid leads are to prevent high frequency oscillation being set up. The grid filament capacity—in this drawing it is grid cathóde capacity—is of low impedance to very high frequency. The charge currents would find a big pressure drop across S and this helps to prevent such currents from flowing, if they otherwise would do so.

The resistances are called "grid stoppers".

CHAPTER XX

HIGH FREQUENCY AMPLIFICATION

IN view of the difficulty of detecting small currents and small voltages because of the "square law" of the detectors, one amplifies the carrier wave before detection. In the early days the triode was used, and it often burst into oscillation, because of the plate-to-grid capacity making it a Tuned Grid Tuned Plate Oscillator. To overcome this, neutralising circuits were used, one of which is shown in Fig. 118.

The grid may have the usual tuned circuit across it, to filament, but the essential feature is the very small neutralising condenser N, which is connected between the opposite end of the plate coil to the one on the plate and the grid as shown.

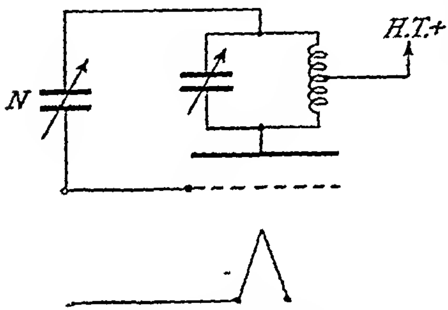


FIG. 118.—NEUTRALISATION.

The H.T. is put on at the middle of the coil or thereabouts. Regarding this as a point of fixed potential, if the plate pressure rises during one half of the wave sending a capacity charge current to the grid, through the internal plate to grid capacity of the valve, the other end of the coil falls in potential, and because it falls, it draws a reverse current through N and so the grid is not affected and self-oscillation is prevented. Capacity N equals Valve Plate Grid Capacity.

The Use of the Tetrode.

The screened grid valve, or tetrode, has a screen between the grid and plate. This isolates the two and prevents oscillation. The screen grid should be kept at a high tension somewhat under that of the plate and should be connected

to filament by a condenser to keep its voltage from fluctuating at the high frequency being amplified.

In addition to avoiding oscillation, the tetrode, having a high impedance, gives far better amplification thus: Suppose the tuned plate circuit has an impedance at resonance of 50,000 ohms. Suppose the triode has a mutual conductance of 3 ma /volt and a plate impedance of 10,000 ohms. The μ is 30. If the tetrode has the same value of g, i.e. 3 ma /volt, its impedance will be much higher, say 200,000 ohms. The μ is now 600.

The 50,000 ohms of the tuned plate circuit makes little difference to the tetrode and the results of the calculations of Stage gain are seen to be:

$$\text{Triode: } \frac{30 \times 50000}{60000} = 25.$$

The tetrode: $\dfrac{600 \times 50000}{250000} = 120$, and it would be more still, if the external circuit had a higher quality, i.e. higher impedance in tune. The circuit is shown below.

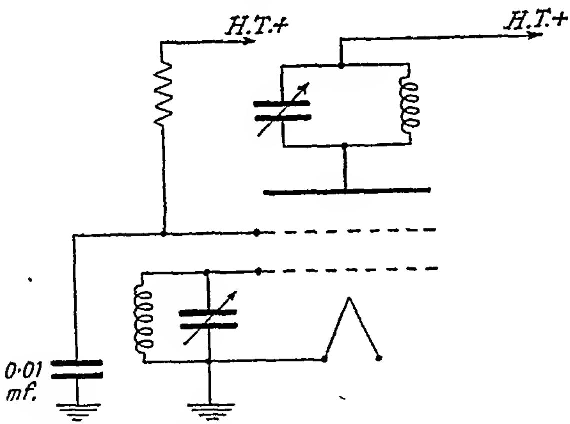


FIG. 119.—THE TETRODE FOR H.F. AMPLIFICA

The coils may, and usually will, need to be sc each other in metal cans, and also the grid lead ... be run in a screened sleeve and the screen earthed

The H.F. Pentode.

The high frequency pentode is as easy to use as the tetrode, because the makers usually connect the suppressor grid to filament or cathode inside the valve. Both valves give high amplification, and the grid is usually lead out at a top cap or else the plate is, instead. This separates these leads from each other, and helps to prevent self oscillation.

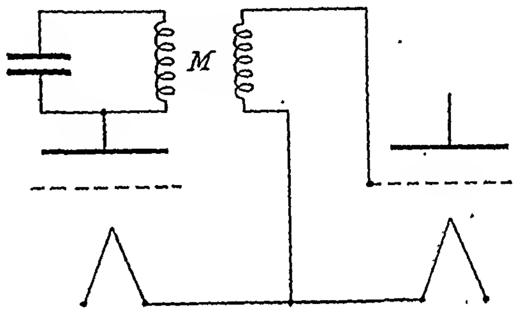


FIG. 120. H.F. TUNED TRANSFORMER COUPLING.

A tuned grid circuit may also be used to couple one valve to another, or else a tuned transformer may be used, as in Fig. 120. Both grid and plate coils may be turned with separate condensers. This is, then, a band pass filter coupling circuit. A still better method is link coupling, which is also

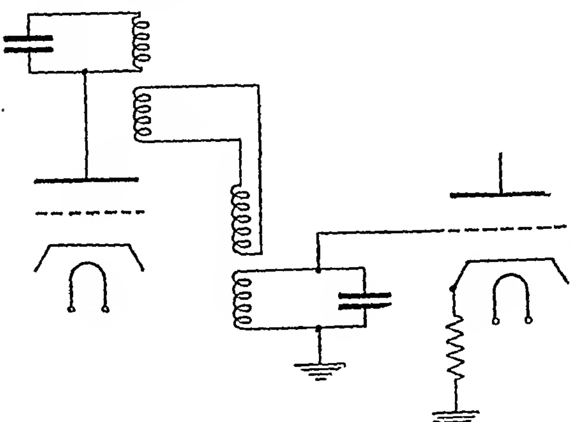


FIG. 121. "LINK" COUPLING.

a band pass circuit if the coupling coils in Fig. 121 have the correct coupling for it.

Link Coupling.

The link coils consist of a few turns coupled to the main coils. The leads from one link coil to the other are crossed over to avoid the wire loop generating magnetic fluxes, and inducing curre ts in adjacent conductors. Being coils of few turns, the link coils are of low impedance. This means heavy currents and low voltages, giving freedom from setting

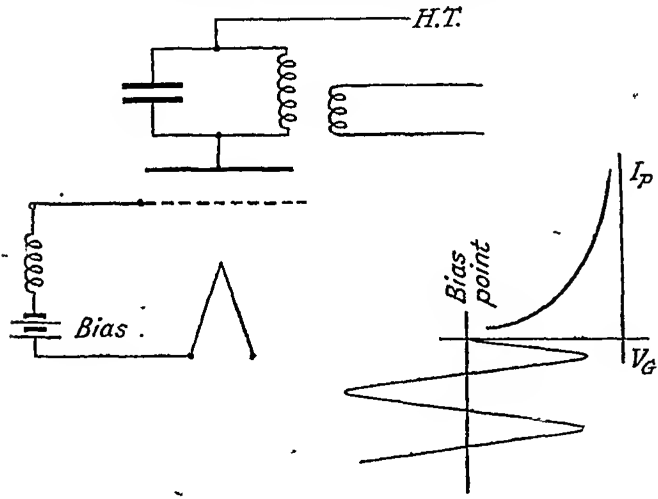


FIG. 122.—CLASS C AMPLIFICATION.

up interference with other circuits. The drawing incidentally shows indirectly heated valves.

Some of these circuits, all in fact so far described, can be used for amplifying a modulated wave as the couplings, especially the band pass couplings, give the necessary conditions. When it is desired to amplify an unmodulated carrier, Class C amplification is excellent, as it makes a small valve do the work of a big one.

The link coupling circuit is particularly suitable for this, as the essence of Class C amplification, as it is called, is a tuned

plate circuit not over damped. The valve has a bias much on the left of the bottom bend and the grid works on the peak of the input wave only. (See Fig. 122).

The plate circuit is a reservoir of energy and its oscillations would persist for a time if the input were cut off. The tuned circuit is called a "tank" circuit and the coil a "tank" coil. It is kept in oscillation by the peaks of the input waves. The grid may go positive or it may not, depending on amplitude of grid input.

The circuit is efficient as far as the valve is concerned because high voltages and powers in watts are not wasted on the plate. The valve is made suddenly to conduct well by the peak of the input wave. This means that most of the H.T. voltage is across the tuned circuit and very little across the valve.

When there is much voltage on the plate itself the valve is not conducting, because the grid is very negative and so there is no plate current. Since Power = Voltage × Current there is little power wasted in the valve itself at any part of the cycle.

If the grid is made positive in a large valve, a good deal of power is used on the grid and a "mains power unit" may be needed to supply the grid bias. A stage with bias derived from the charging of a condenser in the grid lead must not have the H.T. supply on the circuit unless the input wave is already on the grid. Otherwise much current will flow under high voltage on the plate and harm the valve.

CHAPTER XXI

MATCHING IMPEDANCES BY A TRANSFORMER

IN the early days, it was a well known rule that the greatest power in watts was obtained from a battery in a resistance whose value was equal to the internal resistance of the battery. A low resistance gave poor voltage across it and a high one poor current in it. In each case one multiplier of $W = VI$ was small.

The current is $\dfrac{E}{R + x}$ where R is the internal resistance and x the external. The voltage on x is $\dfrac{xE}{R + x}$ and the power $\dfrac{E^2x}{(R + x)^2}$ (Differentiating and equating to *o* in the usual way gives the result x must equal R for maximum power. There seems no easy way to prove this apart from calculus.)

When dynamos were invented the same rule was dragged in "by the horns" to make the armature resistance equal to that of the load. Half the power is wasted *Inside* the dynamo in that case. Edison showed this was wrong policy, and as the maker can give the dynamo a very low resistance the rule should not be used. A valve maker cannot make valves of as low an impedance as he wishes; so with a given valve one is back to the old battery technique, but with A.C. not D.C. using transformers to "alter" impedances.

Suppose now one has a load of impedance 10 ohms and one connects a transformer of 2:1 step down-ratio, applying 120 volts to the primary. The secondary voltage will be 60 and the current 6 amps. in the 10 ohms by Ohm's Law. Assuming no losses and negligible magnetising current in the transformer, i.e. a "perfect" transformer, often called an ideal one, the primary current is 3 amps. In an ideal transformer the primary current will be in phase with the applied P.D. if the load on the other side is a pure resistance. The circuit consisting of the resistance and transformer "looks like" a resistance of

Here L is the primary inductance but L–M is the primary leakage inductance. If L is small, M will be, and M is across the line which would be bad. .If L is very big so is L–M and blocks the current on each side of M in the equivalent circuit.

The two pieces L–M are called leakage inductance. This is a device for understanding how the leakage flux and magnetising flux, affects a 1 : 1 transformer. With other ratios, just multiply voltage and current in the second winding by the turns ratio. As well as having the correct turn ratio, in practice, since a transformer has only a finite inductance in its windings this ought not to be too low or else the windings tend to "short circuit" the voltage being transformed. The inductance should not be much too big either or the L–M being big will keep current from entering the windings.

Proof to Maximum Power Rule: External Resistance Equals Internal.

This proof without calculus uses rules which are useful when calculus is used.

As shown above Power $= \dfrac{E^2x}{(R + x)^2}$

If this is to be a maximum since E is a constant neglect the multiplied E^2 so $\dfrac{x}{(R + x)^2}$ must be a maximum. If so, when turned upside down $\dfrac{(R + x)^2}{x}$ must be a minimum.

Multiply out and it is $\dfrac{R^2}{x} + 2R + x$.

Since R is constant one could divide by R and $\dfrac{R}{x} + 2 + \dfrac{x}{R}$ should be a minimum. So $\dfrac{R}{x} + \dfrac{x}{R}$ the variable terms must be a minimum. Call $\dfrac{R}{x}$ a new variable Z. Then $Z + \dfrac{1}{Z}$ is to be a minimum.

So we have

$$\text{A Number} + \text{Its reciprocal}$$

to be a minimum. It follows $Z = 3$ say gives the same answer as $Z = \frac{1}{3}$. Also Z cannot be big for $Z + \frac{1}{Z}$ to be a minimum. It must be near to 1.

Suppose it is $\frac{11}{10}$. Then $Z + \frac{1}{Z} = \frac{11}{10} + \frac{10}{11}$

This is $1 + \frac{1}{10} + 1 - \frac{1}{11} = 2 + \frac{1}{10} - \frac{1}{11}$.

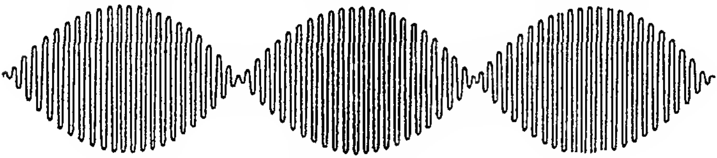
This is greater than 2 because $\frac{1}{10}$ is bigger than $\frac{1}{11}$. It will always be a bit greater than 2 unless Z or $\frac{R}{x}$ is equal to 1 when there is a proper minimum of $\frac{R}{x} + \frac{x}{R}$ meaning Maximum Power.

$\frac{R}{x} = 1$ means $R = x$, which proves the theorem.

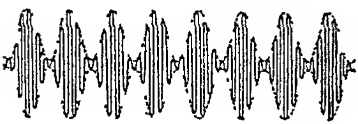
CHAPTER XXII

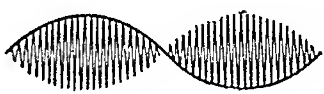
HETERODYNE DETECTION

WHEN a carrier is sent out unmodulated, after detection it cannot be heard because the result is D.C. If, however, an interrupter is put in to chop the wave up at an audio frequency, say 500-wave trains, i.e. pulses of carrier frequency per second, this will give an audible note in the receiver every time the key is held down to send a dot or a dash. Another method of getting a musical note is to employ



Time Base of Oscillograph Fast





going the same way. The result is that they sometimes add and sometimes oppose each other, as shown in Fig. 124.

The Study of Beats.

The beat wave which is the addition of the two plain ones is not a modulated wave, for the tops do not lie on a sine curve at all but form a series of hoops, i.e. with a sharp corner at the bottom which differs from even a 100 per cent modulated wave, shown in Fig. 125A.

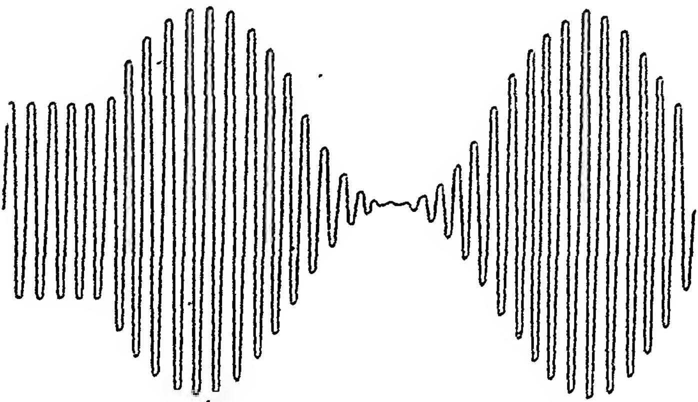


FIG. 125A.—COMPLETELY MODULATED WAVE.

The reason is that a modulated wave has three sine waves in it, not two. It has some "free" carrier. The beat wave has a peculiarity which is not obvious—it is this, while the new "frequency" (if one may use the term, meaning the number of times crossing the zero and back per second) is the average of f_1 and f_2 the waves in the second beat are all upside down in comparison with the waves of the first and third beats and so on. This is seen from

$$\text{Sin } A + \text{Sin } B = 2 \text{ Sin } \frac{A - B}{2} \text{ Cos } \frac{A - B}{2}$$

The 2 shows that the beat wave has twice the amplitude of each of the separate waves, the Sin $\frac{A + B}{2}$ shows that the wave

as regards rate of vibration has a "frequency" $\frac{f_1 + f_2}{2}$ and the

MULTIPLIED Cos $\frac{A - B}{2}$ shows the slow variation to be a cosine for the shape of the envelope; but a cosine changes from + to − after the first quarter cycle, so the true envelope is not the series of hoops but the thick line shown in Fig. 124.

That is why we say that the beats are alternately "right" and "wrong" way up. If now some Sin $\left(\frac{A + B}{2}\right)$, which in modulated waves is the carrier, is added, then beats 1, 3, 5, raise the carrier amplitude and beats 2 − 4 − 6 depress it, giving the usual modulated wave shown in Fig. 125B.

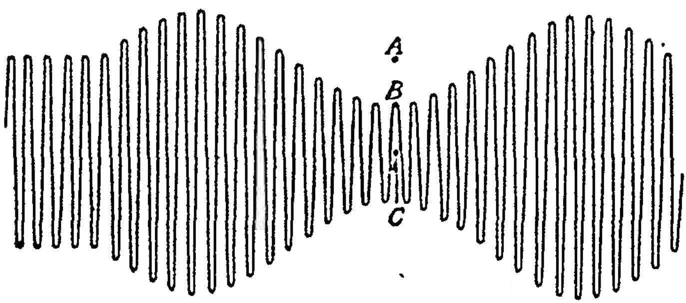


FIG 125B —A COMMON MODULATED WAVE.

For heterodyne reception the local oscillator may be a separate valve and there may be a buffer stage, i.e. an extra valve between the oscillator and the detector to prevent the incoming wave pulling the oscillator into step when the beat note would disappear altogether. (See Fig. 126).

The Superheterodyne Receiver.

This receiver like the turbine was invented early, made little headway because of lack of mathematical work and lack of understanding of the exact principles involved. Both fell into disuse and were "rediscovered," finally becoming very popular and successful.

The principle is that a local oscillator is used to give a

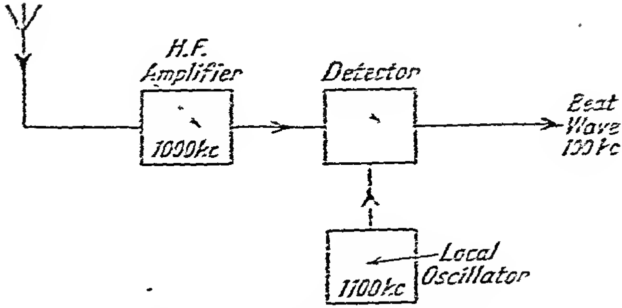


FIG. 126.—HETERODYNE DETECTION.

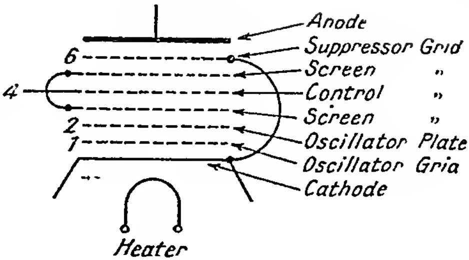


FIG. 127.—THE OCTODE.

electrons up in a cloud. The result is that the second grid and plate form a valve which has a mutual conductance controlled by the first grid. A further development was to put a grid above the first so that these can form a Meissner or other oscillator. The grids are named on the sketch, Fig. 127.

The difference of principle is that the intermediate frequency currents are found in the anode or plate circuit because the plate current contains a term which is proportional to V_{G_1} times V_{G_4} or $(\sin W_o t)$ $(\sin W_c t)$ which is $\frac{1}{2}$ Cos $(W_o - W_c)t$ $- \frac{1}{2}$ Cos $(W_o + W_c)t$.

As the oscillator swing is increased, a sort of overloading takes place, so that the volume of intermediate frequency current in the anode is no longer quite proportional to the oscillator voltage, but apart from that, real multiplication takes place, even when the valve with fixed D.C. voltages on G_1 gives a series of straight lines when curves of V_{G_4} against Anode Current are obtained.

In practice, the characteristic lines are curved to give automatic volume control but this is bad policy for that could be obtained without curving valve characteristics at all.

In automatic volume control one works on the steep or flatter part of the characteristic to vary the amplification.

Intermediate Frequency Filters.

To filter the intermediate frequency and pass it on to be amplified, tuned transformers are generally used. After this the volume may be as high as several volts, so diode rectification may be used to advantage. Sometimes the diode is made part of the output valve.

Advantages of the Superhet.

The outstanding advantage is that one has a band pass

filter or even several such filters, which greatly adds to the selectivity of the set, without having to retune these when a fresh station is wanted. The oscillator must be retuned, and the H.F. circuits; leaving a constant difference (which is the I.F.) between the two. Further, since the I.F. is a different frequency from the signal frequency, the risk of feed back in the amplifier from later to earlier stages with consequent bursting into self oscillation, is smaller than in a straight set of equal amplification. Probably the only disadvantages of the superhet which are inherent in it are the complication, and what is called the Second Channel Interference which is caused by a station which has its frequency on the "other side" of the oscillator frequency from the station being heard,

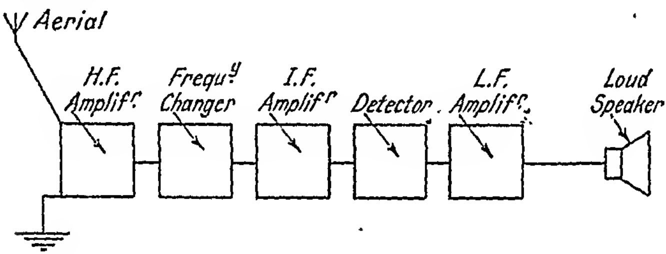


FIG. 128.—THE SUPERSONIC HETERODYNE RECEIVER FOR SPEECH AND MUSIC.

and having an equal spacing in frequency from the oscillator to the desired station. That makes the I.F. the same for the two stations, so that both could, unfortunately, be heard together.

The block diagram of a superhet is as shown in Fig. 128.

The oscillator portion of the octode is now frequently made a separate part of the same valve from the mixer portion which becomes a hexode. The triode oscillator grid is connected internally to the second input grid of the mixer. There is for one thing less danger of pulling into step with these triode hexodes.

Selectivity.

With the usual form of resonance curve the peak is sharp if good quality coils are used. For example, if $Q = 200$ then

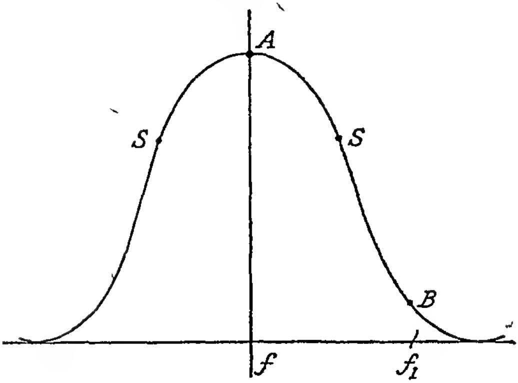


FIG 129A.—SELECTING A WEAK STATION OVER A STRONG STATION

the current in a series circuit falls to 70·7 per cent of the resonance current when the carrier is half of one per cent off resonance. At a carrier of a megacycle that is 5,000 cycles. Since a carrier modulated by 5,000 cycles has side bands 5,000 c/s on each side of the carrier, the two si cor-responding to a 5,000 cycle tone will be reduced ent of the full strength with one stage of tuning alone. The overall resonance curve of a receiver needs to be very sharp, because all the transmitters which are working generate voltages in the aerial of the receiving set, and only the tuned circuits in the receiver prevent one

carrier wave of the desired station is received across the tuned circuit at strength A but the unwanted one is received at strength B if both stations are equally strong in the district round about the receiver. In practice that is not so; one often wishes to cut out a strong local station and hear a distant and, therefore, weak one. This either means more tuned stages or else a heterodyne principle. In a superhet

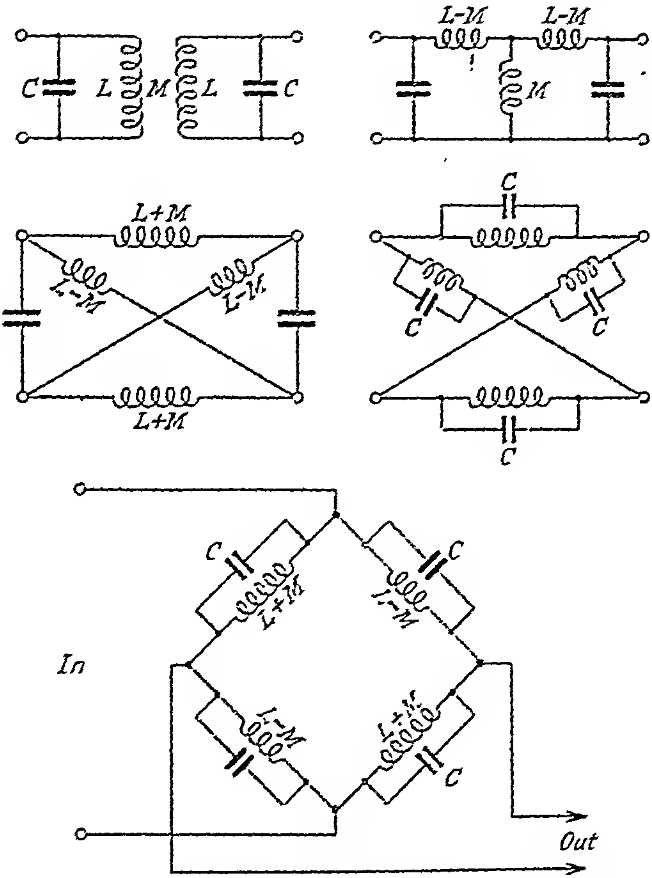


FIG. 130.—CIRCUIT EQUIVALENTS OF TUNED TRANSFORMER.

the *IF* transformers form band pass filters. The resonance curve of such a filter is shown in Fig. 129 (*b*).

The effect of using plain tuned circuits sharply tuned to give good selectivity is to reduce the voltage of the side band frequencies of the high notes. Being further from the carrier than the low notes they come lower down the steep sides of the resonance curve, as at *S S* in Fig. 129 (*a*). The result is called "side band cutting" and means a loss of high notes in music and of the consonants of speech.

The two side band frequencies corresponding to a pure musical tone and of strength *S* as a voltage on the tuned circuit heterodyne each other to produce a beat and as there is the free carrier present they form up as a modulated wave to go to the detector.

It is not easy to see how it is that the tuned transformer is a band pass filter but it can be proved from the fact that all the circuits shown in Fig. 130 are equivalents. That is to say, they act exactly alike whatever the nature of the source, the nature of the load, and the frequency. The final circuit is a bridge circuit which is much "out of balance" at the frequency of resonance of $(L + M)$ and C in parallel, giving a big output voltage. It is much out of balance again at the resonance of $L–M$ and C in parallel—a higher frequency.

The resonance curve can have two peaks, one on each side of the carrier or intermediate frequency to which the *LC* value of the separate windings is tuned. The circuit is equivalent also to a well known band pass filter used in telephone work. From such theory it is evident that tuned transformers would work better all connected in cascade, followed by the valves rather than having a valve, an *IF* transformer, another valve and so on.

To overcome the side band cutting, tone control in the L.F. stages is quite common, and is superior in practice to receivers without it.

Band pass filters are well known in "carrier" telephony for putting several conversations on one pair of wires.

the upward edge B of the cylinder. As it approaches, it experiences a force which is backwards (i.e. right to left) and also downwards. After passing the ring it is forwards and downwards. The result is to bend the path downwards as a convex lens bends a ray of light downwards. The effect is to bring the beam to a focus. Indeed the same mathematical formulas describe both the electronic and the optical case, a truly remarkable fact.

The next thing is to deflect the beam; and a pair of horizontal plates will deflect the beam in a vertical or Y direction as it is called. (See Fig. 132).

There are also two plates side by side to deflect the beam sideways, so that a voltage applied to the second set of plates

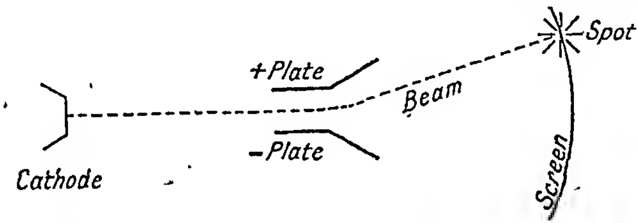


FIG. 132.—THE DEFLECTOR PLATES IN THE OSCILLOGRAPH.

gives an X motion which is independent of the Y motion produced by voltage on the Y plates.

A steady voltage just moves the spot to another position and makes it stay there, but one ought to beware of letting the spot stand still because it "tires" or "burns" the screen in that place. In order to make a visible picture one sweeps the spot from left to right and back by putting periodic voltage on the X plates. To draw a graph of a given voltage, one then puts this second periodic voltage on to the Y plates at the same time. The spot moves in a curve which can be the desired graph. Happily the deflection in any one, and so in both X and Y directions, is proportional to the voltages at that instant on the X and Y deflector plates.

To draw a graph of a voltage wave to a time scale on the axis of X one must apply a voltage to the X plates which is proportional to "time". Then since deflection is proportional to voltage, we have:

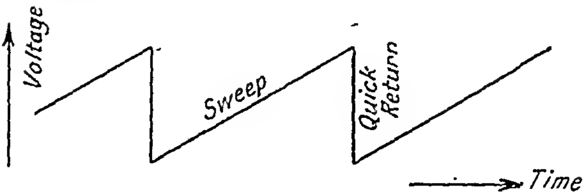


FIG. 133.—GRAPH OF VOLTAGE REQUIRED FROM A TIME BASE CIRCUIT.

Deflection proportional to Time, which is what is wanted. The "sweep" voltage must have a saw-tooth form shown in Fig. 133.

Synchronisation.

The saw tooth wave sweeps the spot across the screen as the wave to be viewed moves it up and down. Even at a low frequency the wave is described too fast to be seen so it is made to go over exactly the same ground again and again. The picture then appears stationary for the same reason that a motor car wheel may in the cinema—the next spoke comes into the same position just as the camera flicks.

The wave being viewed is made to trigger the time base just to help the two to keep step, otherwise the picture of the wave as seen on the screen appears to move slowly backwards or forwards.

The circuit for generating the saw tooth wave is usually mounted in the oscillograph case.

Time Base Circuits.

The simplest way to generate a saw tooth wave is to charge a condenser with a steady current and discharge the condenser at intervals. The plate current of a pentode is fairly constant, even when the voltage across it falls (See Fig. 134), when the condenser begins to charge.

The condenser is shunted by a special valve called a gas-filled relay, which discharges the condenser when it reaches a certain voltage.

The modern circuits are, however, of the multivibrator type described later.

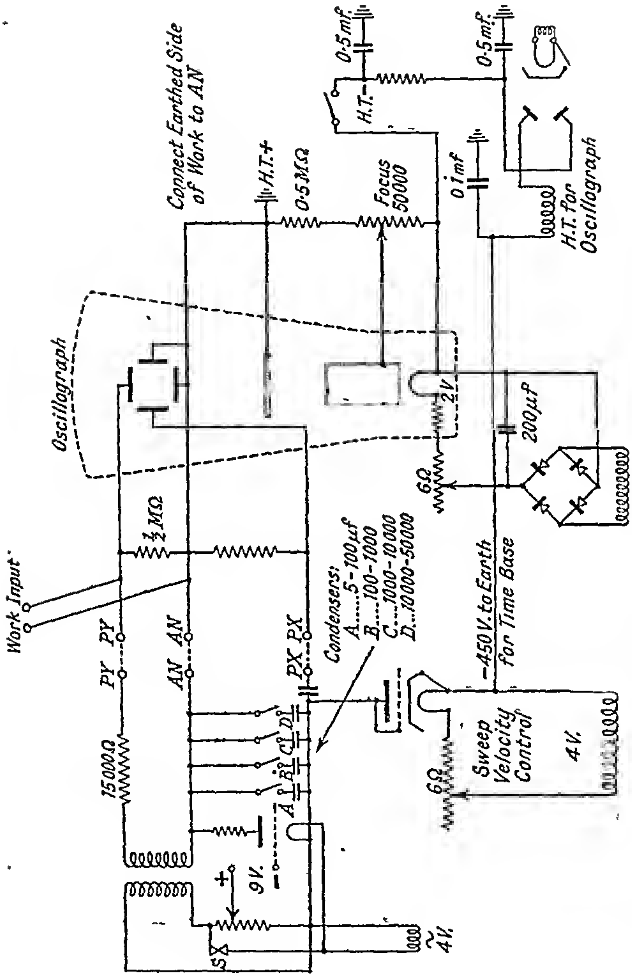


FIG. 134.—WESTERN ELECTRIC EARLY TIME BASE CIRCUIT.

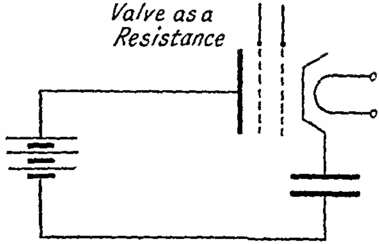


FIG. 135.—TIME BASE CIRCUIT SIMPLIFIED.

When looking at a wave to see what shape it is, a series of gently sloping lines across the screen means the time base is far too fast. A series of close vertical spikes usually means it is too slow. A change of condenser provides a coarse control of the time base frequency and altering the grid voltage on the pentode charging the condenser gives a fine control. The modern time base will sweep at a quarter of a million sweeps per second.

In starting an oscillograph, first put it out of focus in case the time base is slow to start. A wide blurred patch of light will not harm the screen. After use do not turn the "velocity" and "condenser" controls of the time base to "off," but turn down the "brilliancy" of the beam only.

TELEVISION.

In the home television receiver, an oscillograph is arranged with the spot slowly moving down the screen but rapidly moving to and fro across it as one reads a page of print, only much faster. The incoming wave alters the brightness of the beam and this makes the picture. There is a spot of light "scanning" the person or scene to be televised at the transmitter. The reflection is used to control the size or in other words to modulate the outgoing wave from the television transmitter station.

Different systems vary much, and the original scanning spot at the transmitter has been done away with.

Its place is taken by a steady even light—as used in film studios.

ELECTRON MICROSCOPE.

The cathode ray oscillograph has been developed into a new and wonderful microscope of exceptional magnifying power.

CHAPTER XXIV

THE LOW PASS FILTER

THE simple Low Pass Filter is a ladder network with condensers for "rungs" and coils between rungs as in Fig. 136.

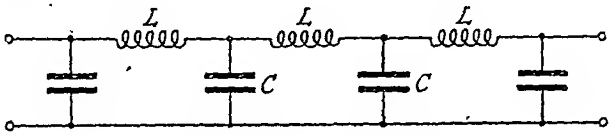


FIG. 136.—THE LOW PASS FILTER.

The network has the remarkable property that currents of any frequency below a critical value, which we may call f_o will pass freely, but currents of frequencies above the cut-off will not pass without being much weakened. The value of f_o is given by $f_o = \dfrac{1}{\pi\sqrt{LC}}$

In practice the far end of the filter must be closed by a load, and the correct load resistance is $R = \sqrt{\dfrac{L}{C}}$

Design of Filters.

Usually one knows the cut-off frequency f_o desired, and also the load resistance R; and one wants to calculate coils and condensers to build the filter. Multiplication gives the condenser value thus:

$$Rf_o = \frac{1}{C\pi} \text{ or } C = \frac{1}{\pi Rf_o}$$

and division of the two formulas gives

$$\frac{f_o}{R} = \frac{1}{L\pi} \text{ or } L = \frac{R}{\pi f_o}$$

Example 17. Design a Low Pass Filter to have a cut-off frequency of 640 c/s and a "characteristic impedance" of 240 ohms, i.e. work into a 240 ohm load.

$f_o = 640$ and $R = 240$ so $L = 120$ *mh* and $C = 2\ \mu f$.

Termination of a Filter.

It is desirable to terminate a filter in a coil of half the full impedance, meaning half the full inductance, or else a condenser of half capacity. To build a filter with one coil and two condensers for the above figures use two end condensers of value $\frac{1}{2}c = 1\ \mu f$. The filter is then as shown in Fig. 137.

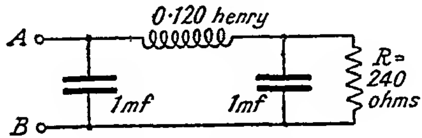


FIG. 137.—A FILTER SECTION.

To test the action of such a filter it is "closed" by a resistance of value R and supplied with a current at fixed voltage but of variable frequency across AB.

One measures voltage across the resistance R and the ratio of oscillator voltage across R gives the "insertion loss" due to putting the filter between the oscillator and the lead.

The insertion loss is strictly:

$$\text{Log}\frac{\text{Voltage on } R \text{ Without Filter}}{\text{Voltage on } R \text{ With Filter}}$$

An interesting experiment is to apply a square wave to the filter and cut off all above the fundamental by arranging the applied frequency to be just under f_0. Then a sine wave is seen on an oscillograph connected across R. With a higher value of cut-off, i.e. less L and C, the fundamental and a third harmonic may be seen.

The Characteristic Impedance of a Filter.

The characteristic impedance of a line (or a filter) may be defined as the impedance measured at the near end terminals when it is infinitely long. Or it may truly be said to be the geometric mean of two measurements on any length of the line, short or long; one being a measurement of impedance with the far end open circuited; the other when the far end is short circuited.

That is transmission line theory. Yet another definition

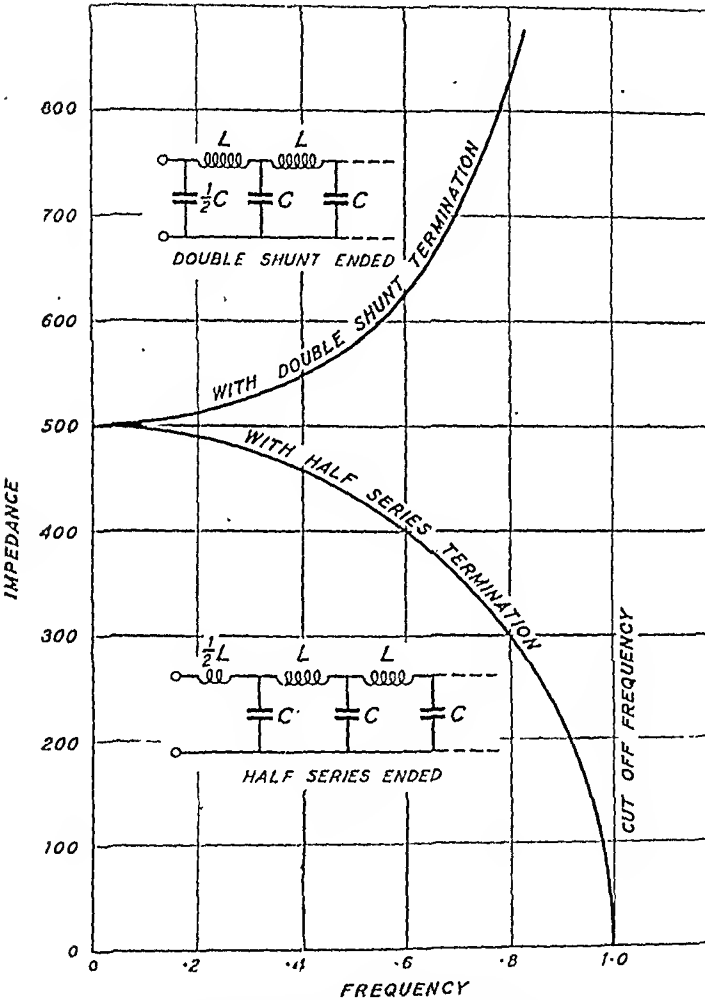


FIG. 138.—IMPEDANCE CURVES FOR THE LOW-PASS FILTER. (500Ω NOMINAL IMPEDANCE).

arises from the first one. It is this: If a line or filter has apparatus (it may be merely a resistance) equal to the characteristic impedance connected to the far end, then measurement of the impedance at the near end is a measurement of the characteristic impedance. In general characteristic impedance varies with frequency.

In a low pass filter the nominal value which holds for very low frequencies is $\sqrt{\frac{L}{C}}$. Here L is the inductance of a whole coil in henrys and C the capacity of a whole condenser in farads. The answer is *so* many *ordinary*—that is, non reactive—ohms. This figure is the same whether the filter begins with half a coil or half a condenser. In the former case however, as frequency is raised towards the cut-off value the characteristic impedance falls to zero ohms: (the diagram is a quarter of a circle). The filter which begins with half a condenser, on the other hand, has a rising impedance curve. The impedance is the "reciprocal" always of the former case: that is to say, a filter with a cut-off of 1,000 cycles measured at 866 cycles, and having $\sqrt{\frac{L}{C}}$ equal to 500 ohms will fall to 250 ohms if half coil terminated, i.e. half 500 ohms. The filter terminated by half a condenser will rise to double 500 ohms, i.e. 1,000 ohms at 866 cycles.

These are characteristic impedances, showing the value to avoid reflections. Filters still work when not correctly terminated.

Their theory is a little study in itself and there are text-books dealing separately with the subject.

CHAPTER XXV

DIRECTION FINDING

THE ordinary frame aerial is directional since it must be turned so that the magnetic flux from the transmitter will cut it, if voltages are to be generated in the turns.

The lines of magnetic flux are in ever expanding circles round the transmitter and the greatest effect is obtained when the plane of the frame forms a radius of the circle. See Fig. 139.

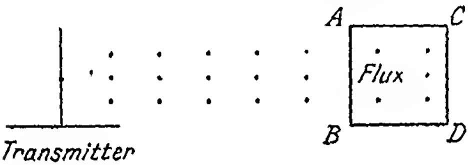


FIG. 139. THE STRONGEST POSITION FOR A FRAME.

Certainly the flux cuts the side *AB* and also cuts *CD* producing voltages in the same vertical direction but opposing in the turns of the loop. When the wave is at a maximum or peak value of the sine curve at *AB*, however, it is not a maximum at the place *CD*; thus there is a differential action. A better way to think of it is the total flux enclosed by the turns. If the frame is turned, looking at a plan view shows that the flux embraced is reduced in the ratio 1 : Cos θ. See Fig. 140.

If then one plots the strength received on a polar diagram

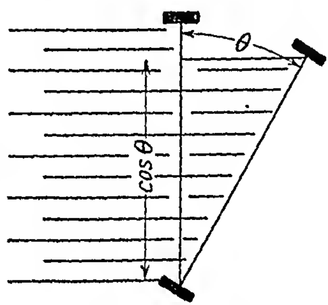


FIG. 140.—THE FRAME AERIAL. Note that when this is turned through the angle θ from its normal position the received signals are weakened in the ratio of 1 to Cos θ.

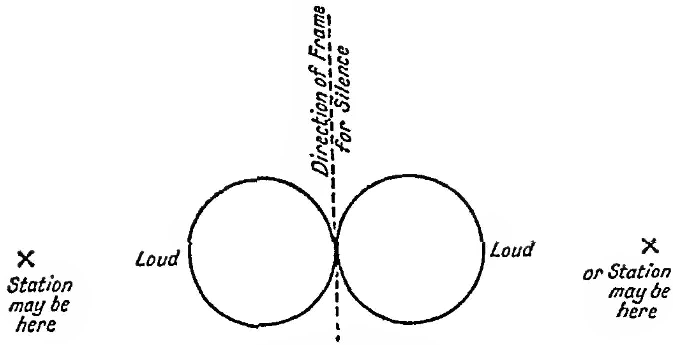


FIG. 141.—ORDINARY FRAME AERIAL SHOWING TWO POSITIONS OF SILENCE.

the equation is $r = \cos\theta$. On such diagrams there is a point, the pole and a line through it. The "r" is the length of the "radius vector" from the pole and the angle in the equation is the angle between the radius vector and the fixed line.

The diagram for $r = \pm \cos\theta$ is shown in Fig. 139. It is a couple of circles.

There are two positions of "zero signal" 180° apart so if one turns the frame round until there is full volume one knows that the distant station is along the line of the frame but one does not know which direction it is, because it may be forwards or backwards as shown in Fig. 142. The positions of silence are 90° away from the positions A and B.

The drawing is a side, and not a top view, or plan, like Fig. 141.

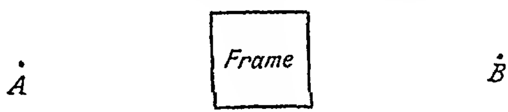


FIG. 142.—TWO POSITIONS OF LOUDNESS OF AN ORDINARY FRAME AERIAL.

(The two Positions of Silence are at right angles to the page.)

The station may be at A or at B in the drawing. If now a vertical aerial is combined with this frame aerial and adjusted by the resistance R (See Fig. 144) to give the same loudness by itself, then since the vertical aerial always gives the same

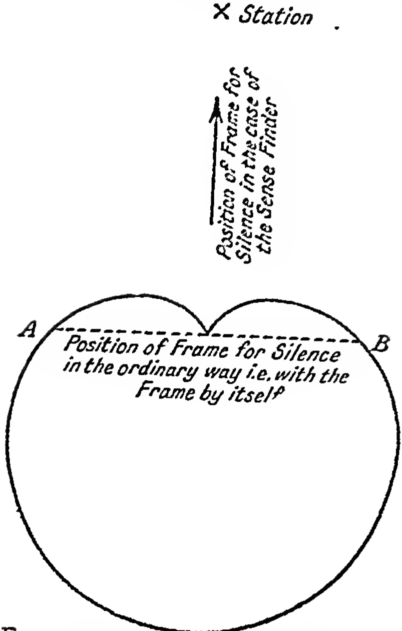


FIG. 143.—DIRECTION FINDER SHOWING THE FRAME IN THE POSITION A.B. OF SILENCE.

volume from whatever direction it may be, in a horizontal plane, the signal of the vertical aerial adds to that of the frame for one half turn but subtracts during the other half turn of the frame, because the current in the frame reverses if the frame is turned through 180°.

There is now one position of silence only; and one should note that the silence is obtained now when the frame is in a direction with its plane directed to the station; one of its full strength positions when it was used alone without a vertical aerial.

The equation now is $r = 1 + \cos\theta$ shown in Fig. 143 and the effect is seen in Fig. 144.

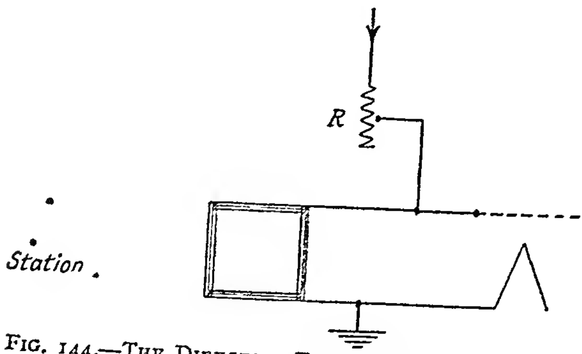


FIG. 144.—THE DIRECTION FINDER WITH ITS SINGLE POSITION OF SILENCE.

CHAPTER XXVI

FREQUENCY MULTIPLIERS

SINCE it is hard to make a stable oscillator as regards frequency, quartz crystals are often used but when these are cut thin for short wave work they become fragile and though they are now being made for frequencies of several megacycles, there is an alternative. A crystal controlled oscillator may be built for a lower frequency than the desired carrier and then the lower frequency wave from the oscillator may be put on to the curved part of the characteristic of, say, a triode and the plate circuit may be tuned to the second harmonic or even to the third harmonic. In this way a multiplication of frequency is secured. The process can be repeated.

The circuits look, on paper, and in the apparatus, very like plain high frequency amplifiers, but the coil sizes and condenser sizes, too, become smaller as one goes from stage to stage of the multiplier.

The Theory.

Consider one stage only at a time.

If a valve characteristic has the form of a parabola containing a term $y = x^2$ where y is the plate current and x the grid voltage, then when x is Sin wt, the plate current contains a term $\text{Sin}^2\, wt$ with other terms such as Sin wt—a copy of the original oscillation—added.

The $\text{Sin}^2\, wt$ term is equivalent to an alteration in average steady plate current together with a *double frequency*, as may be seen from the formula $\text{Cos}\, 2x = 1 - 2\, \text{Sin}^2\, x$, which is well known in trigonometry.

The $\text{Sin}^2\, x = \frac{1}{2} - \frac{1}{2}\, \text{Cos}\, 2x$.

The $\frac{1}{2}$ by itself is the alteration in steady plate current and the $-\frac{1}{2}$ Cos $2x$ is the double frequency. The $\frac{1}{2}$ in $\frac{1}{2}$ Cos $2x$ refers to its amplitude and the $-$ sign and the Cos refer to the phase in comparison with the input wave which does not matter a bit.

Frequency Trebling.

If the valve characteristic contains a cube of x in its algebraic equation, which it does in addition to a square of x, then there is a term in $\text{Sin}^3\,x$ or $\text{Sin}^3\,wt$ in the plate current with other *added* terms such as $\text{Sin}^2\,wt$ and $\text{Sin}\,wt$. As stated, when such terms are added terms one may pick out any frequency by a tuned circuit.

The formula $\text{Sin}\,3x = 3\,\text{Sin}\,x - 4\,\text{Sin}^3\,x$, also well known, shows that $\text{Sin}^3\,x = \frac{3}{4}\,\text{Sin}\,x - \frac{1}{4}\,\text{Sin}\,3x$. The $\text{Sin}\,3x$ is a triple frequency current. The quarter as a factor in $\frac{1}{4}\,\text{Sin}\,3x$ shows that it will not be as big as the double frequency, other things being equal. It all depends on the shape of the $V_G - I_P$ characteristic curve of the valve how big the "a" and "b" of the equation $y = c + kx + ax^2 + bx^3$ for the curve, happen to be.

In practice a stage of plain "amplification" may be introduced between each two multiplier stages to give greater ease of selecting the desired harmonic. These are called buffer stages.

The difference between doubling and trebling is merely in the tuning of the circuit. (See Fig. 145 and 146).

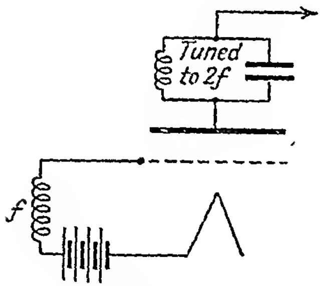


FIG. 145.—FREQUENCY DOUBLER.

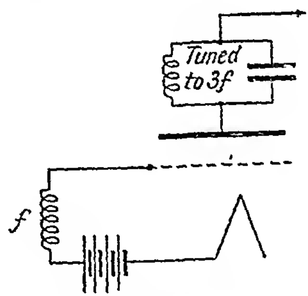


FIG. 146.—FREQUENCY TREBLER.

Quartz Crystals.

The action of a quartz crystal, used in place of the usual tuned coil and condenser in a circuit such as an oscillator or filter is dependent on two electrical effects. One is that an electrical pressure applied to the sides of the crystal causes it to expand or contract sideways. The effect is greatest along the electric axis.

The crystal has its mass and springiness at any frequency, so both are present as regards the mechanical vibration. Thus, electrically the crystal behaves like a series tuned circuit. See Fig. 146A.

FIG. 146A.—THE CIRCUIT EQUIVALENT TO QUARTZ VIBRATING.

The small resistance is settled by the losses, and a great advantage of a crystal is the smallness of this "resistance." The ratio of reactance to resistance, called Q, is enormous.

The quartz plate is coated with metal on each side in order that the applied voltage shall reach the whole plate. This results in a small capacity wherein the crystal is the insulator. The circuit is shown in Fig. 146B.

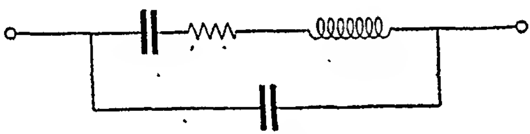


FIG 146B.—THE EQUIVALENT CIRCUIT OF A CRYSTAL (WITH CAPACITY OF PLATING).

This in turn may be "woven" into oscillator and filter circuits but it is a bit like building a house with natural rock rather than with ordinary bricks; more skill is needed because the sizes may not be quite what one would prefer. Loading of the crystal mechanically as by making it support a column of mercury lowers its natural mechanical frequency of vibration and its frequency of electrical resonance, as it is in resonance electrically when it is in resonance mechanically.

The crystal has a very high Q and keeps an oscillator steady in frequency.

CHAPTER XXVII

A.C. BRIDGES

JUST as resistances can be measured on a Wheatstone Bridge with a battery and galvo, inductance and capacity can be measured with a bridge using a source of alternating current instead of a battery and instead of a galvo a telephone. Silence in the phones means a balance. This arrangement using a telephone is good in the audio range down to about 400 c/s when the telephones begin to lose their response. Then, a cathode ray "magic eye" indicator with a filter to cut off harmonics is excellent. The bridge principle is seen

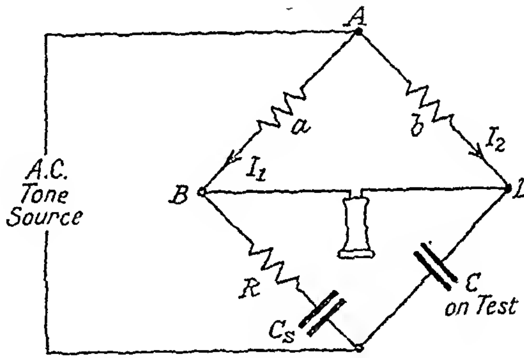


FIG. 147. THE BRIDGE PRINCIPLE. (Ordinary Capacity Test.)

in Fig. 147 for comparing an unknown with a known condenser. The known one may be good, with negligible loss. If it is, one puts a resistance in series with it so that it is as bad as the one to be tested, and this enables a good balance to be obtained.

If $a = b$ then $C = C_S$. It is not enough for the current in "a" to equal the current in "b" so that the voltage (aI_1) equals the voltage (bI_2). *The phases must be the same too,* then if $a = b$ the phase and size of voltage between A and B equals that between A and D and so the voltage between B and D equals zero and there is balance, i.e. silence in the phones.

Some bridges are hard to balance, others are easy. What makes the difference is probably this: In Fig. 148 let AB be the vector voltage across the "a" arm and BD the vector voltage across the "b" arm. If, when either the standard condenser or the resistance R is altered, the one vector moves relative to the other in the direction of the arrow, the bridge will be hard to balance because the difference, which settles the pressure in the detector, will be unchanged.

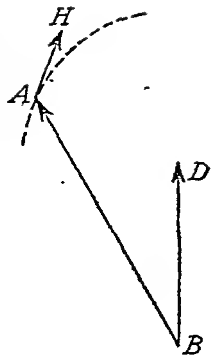


FIG. 148.—VECTOR DIAGRAM SHOWING BALANCING OF A BRIDGE.

If, however, the head A of the vector BA moves in either the direction AB or AD it will be easy to balance because a little motion soon reduces AD or makes $AB = BD$ in length when a phase swing gives balance. To give the proofs of the four bridges in Fig. 149 is outside the scope of this book although a little is said later.

With nothing but a standard condenser and a variable resistance R and a pair of ratios, one can measure almost anything. Bought bridges are usually a bad investment for colleges and universities. They are usually not very accurate, give a too restricted range of measurement, and often work at one frequency only. The method of setting up a primary standard of reactance used to be to use Maxwell's equations to get the mutual inductance between two wire squares. This made mutual inductance the basic standard. Nowadays in the frequency of the "grid" we have a standard frequency of undreamed of accuracy because it can by a synchronous clock be checked against the time "pips," which are settled by astronomy. A frequency bridge of the form shown in Fig. 150 gives $C_1 C_2$ the product of a pair of unknown condensers. Then Fig. 147 gives the quotient $\dfrac{C_1}{C_2}$

It is thought by the author that this will become a standard method. Any frequency which is a multiple of 50 c/s can be compared with 50 c/s mains by putting each on to the separate pairs of plates of a cathode ray oscillograph and

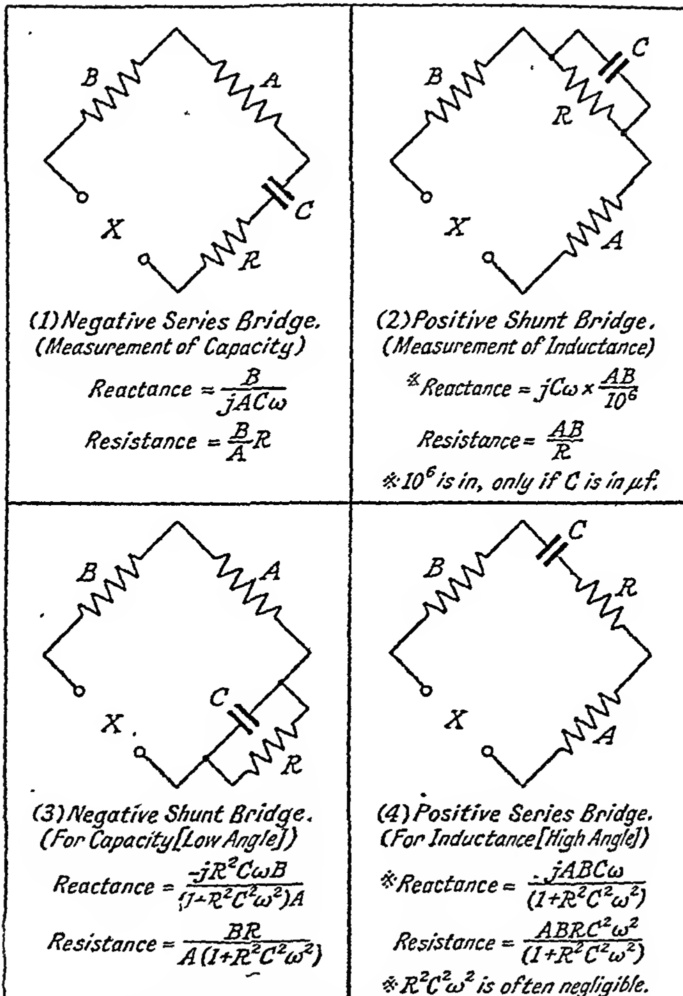


FIG. 149.—FOUR BRIDGES USING CAPACITY STANDARD.

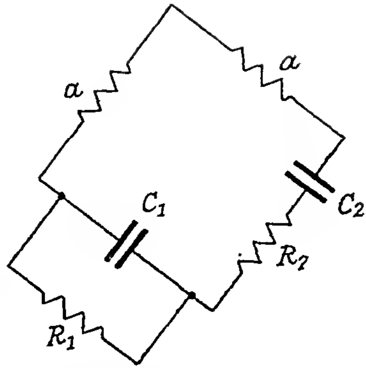
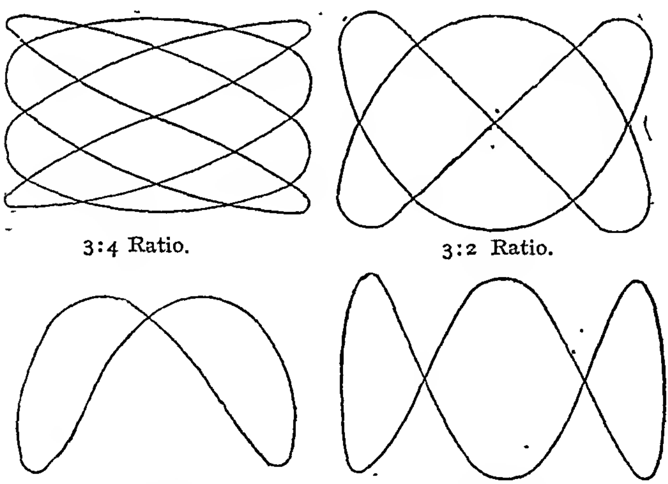


FIG. 150.—ROBINSON FREQUENCY BRIDGE MEASURES C_1, C_2 IF THE FREQUENCY IS KNOWN.

stopping the time base. The Lissajous figure (see Fig. 151) goes round—if there is inaccuracy but an exact multiple makes it stationary. So does a ratio of 3 to 2 say.

Maxwell's Bridge.

This bridge, sometimes called a "Positive Shunt" Bridge because the standard Condenser is shunted by the resistance and also placed at the opposite side of the square to the "unknown," making a measurement of coil or "positive" impedance. It can be made to measure quite small inductances. If the resistance arms are 10^w and 100^w or better



3:4 Ratio. 3:2 Ratio.

2:1 Ratio. 3:4 Ratio.

FIG. 151.—LISSAJOUS FIGURES.

N

31.6 ohms, then a 3-dial box of condensers giving fractions of 1 mf. gives a measurement of fractions of a millihenry to three places of decimals.

By using switches, all four (or five bridges with the frequency bridge) can be made up as one unit. A good detector is necessary. A circuit of one is given in Fig. 152.

The 1 to 30 transformer was a microphone transformer made by S.T.C. Co. for their moving coil microphones. No other seemed free from pick-up.

A good adjunct is a box of low pass filters with cut-offs

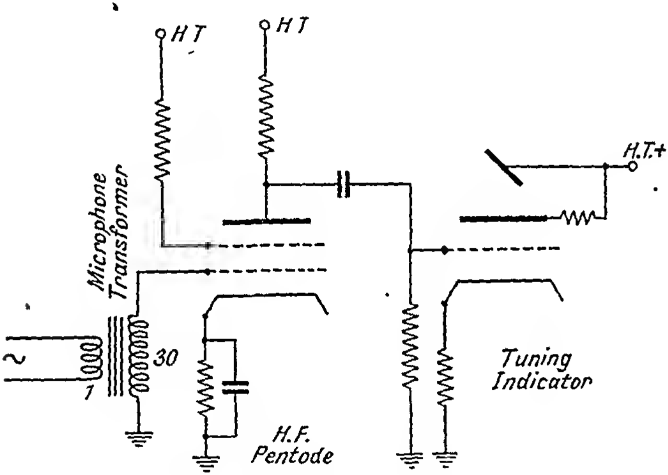


FIG. 152.—A BRIDGE DETECTOR.

going up in the ratio about 3 to 4. If one is 1,800 the next could be 2,400 c/s and so on. Even if the oscillator is good, harmonics may develop in the iron core of a coil on test.

One needs to beware of the resistance boxes which may be unreliable on A.C., especially the 1,000 and 10,000 ohms dials owing to capacity between wires of coils wound non-inductively.

CHAPTER XXVIII

THE COMPLETE RECEIVER

THE following is a description of a simple 3-valve receiver. (See Fig. 153).

There is a tetrode for the H.F. stage, followed by a Detector and one L.F. stage. If battery valves are used, their filaments are put in parallel across the L.T. battery.

The aerial comes to the control grid of the tetrode and the first tuning circuit is a parallel resonant circuit between grid and filament. The filament is earthed. *Often there is a condenser earthing the screen of the tetrode to high frequency currents.* A second tuned circuit is put in the plate of the tetrode, and a ·0002 mf. condenser feeds the H.F. current from the plate to the detector grid. If the detector is a leaky grid detector, the bottom of the 2 megohm leak is connected to the positive side of the filament.

The ·0002 mf. condenser in this case is the grid leak condenser and it also keeps H.T. off the grid of the detector valve. A transformer with a laminated iron core may be used to couple the detector to the L.F. stage. If headphones are used these may be put in the plate of the last valve, unless crystal phones are used.

If it is desired to work a loud speaker, a step down transformer is put between the valve and the speech coil.

Reaction.

Smooth reaction is obtained by feeding the reaction coil through a condenser, and if reaction is poor a high frequency choke may be put to keep H.F. currents from the L.F. transformer and make them go to the coil.

The Loud Speaker.

The usual form of loud speaker is one with a moving coil working on the electric motor principle There is a small coil attached to the moving cone diaphragm. The coil is fed

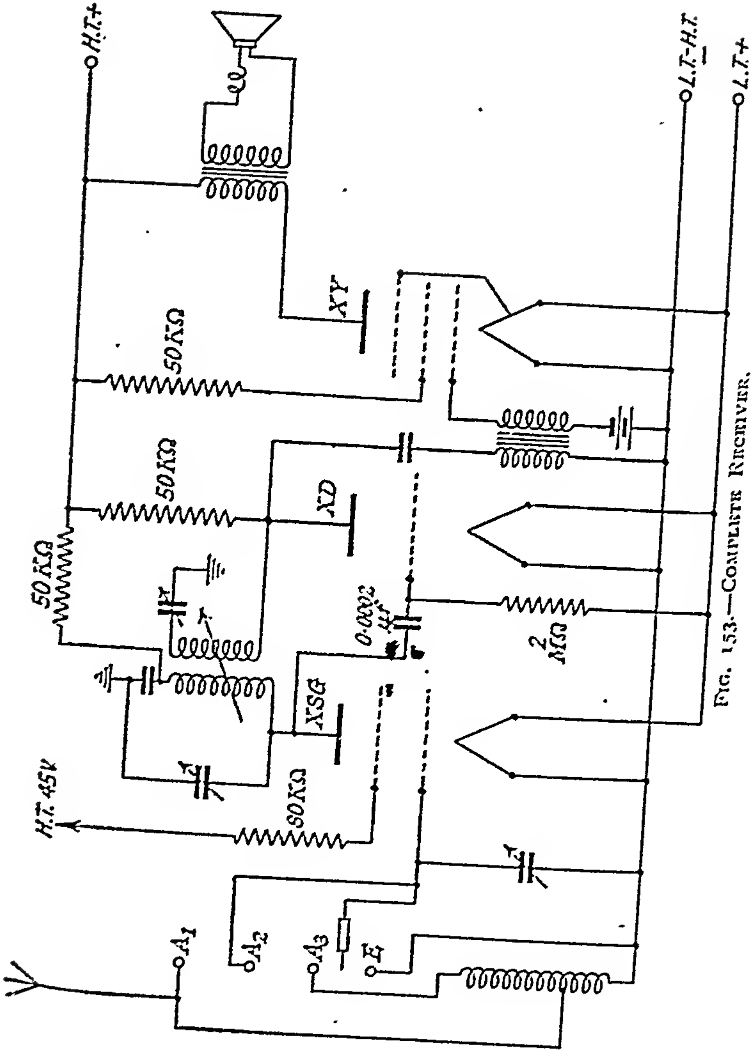


FIG. 153.—COMPLETE RECEIVER.

with speech currents and vibrates in the magnetic field. The energy of the current is chiefly used up in the resistance of the speech coil as heat and in circulating eddy currents in the iron which carries the flux to the coil.

The coil measures like a resistance—almost a pure resistance throughout the speech frequency range and so can be conveniently matched with the transformer. There is a condenser needed to earth the screen of the H.F. valve, as a rule.

In Fig. 153 the aerial may be put in A_1 or A_3.

CHAPTER XXIX

STANDING WAVES

WHEN a wave travelling along a pair of wires comes to the end, if the ends are "disconnected" sometimes called open or "free," the voltage wave is reflected back and it adds on to the original wave causing double voltage. There is no current, however, at the "dis" as might be expected. With a finite length of wire reflections usually take place at both ends and a wave is reflected backwards and forwards like a weaver's shuttle giving rise to a series of waves in each direction.

Like a main road there are two streams of traffic, one going each way. Since sine waves of any one frequency add up

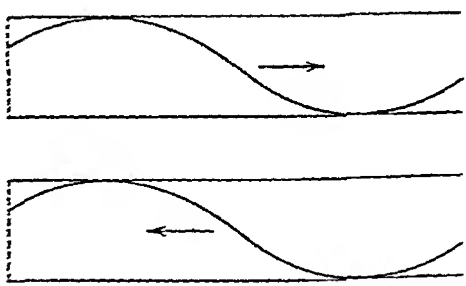


FIG. 154.—TWO TRAVELLING WAVES GIVING RISE TO STANDING WAVES.

to give a *single* sine wave, so they do here, and the result is to give *one* sine wave going from left to right and one going from right to left as shown in Fig. 154.

The voltage on the wires is the sum of these two and a curious thing results from addition. It is this: Addition produces a wave which appears to stand still in space but not in time. The peaks in space (where a lamp put across the wires lights brightly) are places of large alternating voltages. The zero's of the wave in space are zero all the time and are fixed places.

The high frequencies which produce short-waves of say four

metres will give a standing wave such that the peaks are two metres apart, so two wires put across a room work quite well. The electrical vibration drawn as a graph in space along the wires gives the same type of vibration as a piano string in sound. There are moments of no voltage all along the wire. By voltage we mean voltage across the pair of wires. The sequence of events is shown in Fig. 155: the order is 1, 2, 3, 4, 5, 4, 3, 2, and 1, just like the string of a piano. The dotted line is the place where the drawing should end, if it is intended to

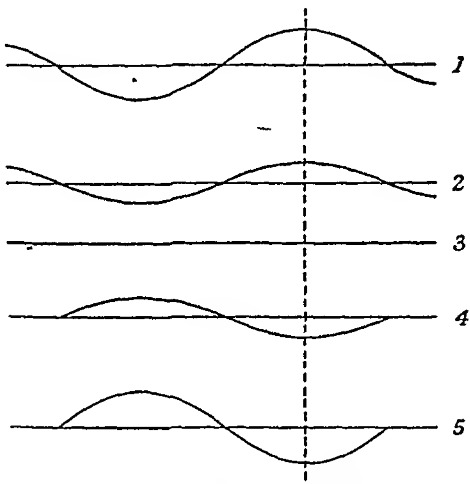


FIG. 155.—STANDING WAVES.

represent a line cut at the far end. A cut here is correct, since the cut end of the line is a place of high alternating pressure—not a zero. As regards the reflection effect, everyone knows what an echo is, the air cannot move through the surface of a rock and so another reflected wave springs up—the echo—adding to the original to give zero motion of the air particles at the rock face. It is the same here. The rock face like the end of the wires is a place of no current but high pressure.

CHAPTER XXX

THE j NOTATION

IN solving problems in alternating currents, there is a simple routine method of calculation. It is called the j notation. This is what one does. One looks at the circuit, and goes all round it writing JLW for each inductance, and

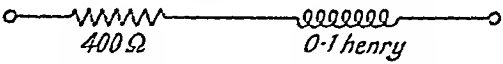


FIG. 156.—COIL IN SERIES WITH RESISTANCE.

$\frac{1}{JCW}$ for each condenser. Only one frequency must be used at once. For example, at 800 c/s a ·1 henry coil is $500j$ ohms and a 2 mf. condenser $\frac{100}{j}$ ohms. The j is the "Square root of minus one".

This means that $j \times j = -1$ always so that a condenser of $\frac{100}{j}$ ohms may equally be written as having $\frac{(-1)\ (-1)\ 100}{j}$ ohms, or replacing one "minus one" by j^2 we have $\frac{(1) - j^2\ 100}{j}$ ohms. Cancel j out and it is $-100j$ ohms.

The arithmetic is simply the algebra of the imaginary and one soon learns the way to manipulate the fractions. Now a word about the underlying reasons.

Mathematicians now use the $\sqrt{-1}$ or the imaginary as it is called. They draw diagrams with x as the REAL axis and the y axis as the UNREAL—thus. (See Fig. 157).

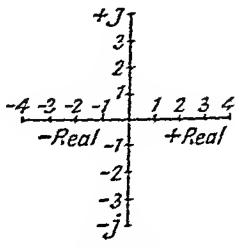


FIG. 157—REAL AND UNREAL AXES.

On such a drawing $3j$ is a vertical line (strictly a point on the $+j$ axis) thus: (See Fig. 158).

In an inductance, the voltage leads the current 90° so one says

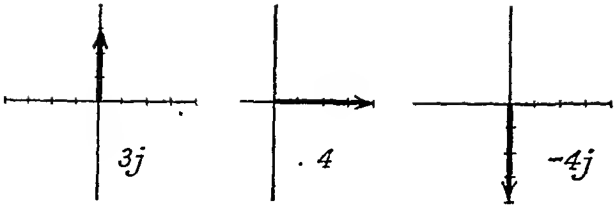


FIG. 158.—THE J NOTATION.

that where $LW = 3$, say, the inductance has an impedance $3j$ because IMPEDANCE may be called VOLTAGE FOR 1 AMP. and the voltage must lead in a coil of negligible resistance by 90°. Resistances are left plain. One uses all the ohms, those with j's and those without, like resistances, but the j's must not be forgotten. Is the coil in series with a resistance of 400 ohms? If so it is $400 + 500j$ for the impedance at 800 cycles. In parallel it is $\frac{\text{Product}}{\text{Sum}}$ but j is always the $\sqrt{-1}$.

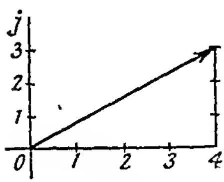


FIG. 159.—IMPEDANCE LAG.

Since current in a condenser leads, voltage lags and a condenser, therefore, has a lagging impedance. A coil of 3 ohms reactance and 4 ohms resistance has an impedance $4 + 3j$ which is shown in Fig. 89.

The hypotenuse is $\sqrt{3^2 + 4^2} = 5$ ohms long and θ is an angle such that $\tan \theta = \frac{3}{4}$ which is 36° 50′ from tables of values of Tan θ.

The impedance may be quoted as $4 + 3j$ or else as $5\underline{/36^\circ 50'}$. Capacitative impedances are written as $5\overline{\backslash 37^\circ}$ and are called negative impedances. The $5\overline{37}$ is equal to $4 - 3j$.

Examples of Working.

Let 10 volts be applied to the coil $4 + 3j$. The frequency will be such as to make $L\omega = 3$ for the coil. (One has to know f to find $\omega = 2\pi f$ in order to say how much j a coil is in the first place.)

In Ohm's Law Current is $\frac{V}{\text{ohms}}$ so here current $= \frac{10 \text{ volts}}{4 + 3j}$ or one may say $\frac{10}{5\underline{/36°50'}}$. Either gives the proper current.

Take the first, the rule is to multiply top and bottom by $4 - 3j$, i.e. the same with reversed sign.

$$\text{Current} = \frac{10\,(4 - 3j)}{(4 + 3j)\,(4 - 3j)} = \frac{40 - 30j}{16 + 12j - 12j + 9}$$

$$= \frac{40 - 30j}{25} = 1{\cdot}6 - 1{\cdot}2j \text{ amperes.}$$

This means 1·6 amps. in phase with the applied voltage, and also 1·2 amps. "$-j$" or lagging 90° behind the applied voltage.

The total current is $\sqrt{1{\cdot}6^2 + 1{\cdot}2^2} = 2$ amps. and the angle of lag is an angle 36° 50′ making Tan 36° 50′ $= \frac{1{\cdot}2}{1{\cdot}6}$

The second way is easier: Current $= \frac{10}{2\underline{/36°50'}}$ The rule is: "divide vector lengths and subtract angles," to divide vectors in the $r\underline{/\theta}$ form. That is a current of $2\overline{\backslash 36°50'}$ amps. or 2 amps. lagging 36° 50′ behind applied voltage.

If a coil with 600 reactance and 40 ohms resistance is in series with a condenser of 500 ohms reactance the whole circuit is:

$$40 + 600j - 500j = 40 + 100j.$$

When coil and condenser are in resonance the $+j$ is as big a number as the $-j$ and it is 40 resistance only.

As a good example of the usefulness of the j notation in deriving formulas let us take the Meissner oscillator.

Proof to the Meissner Oscillator.

The way to find the conditions of oscillation is to begin at the grid and work round to it via the plate.

Let the resistance of the coil in the tuned circuit connected to the plate be R, the plate impedance of the valve R_a and the amplification factor μ. If 1 volt is assumed on the valve grid, the voltage released in the valve is μ volts. This is meant to be alternating, either R.M.S. or Max. values.

The tuned circuit impedance being $R + jL\omega$ and $\dfrac{1}{jC\omega}$ in parallel, is

$$\frac{\dfrac{R + jL\omega}{jC\omega}}{R + jL\omega + \dfrac{1}{jC\omega}} \text{ which is } \frac{R + jL\omega}{jRC\omega - LC\omega^2 + 1}$$

To this R_a must be added as the valve is in series, so the total impedance is $R_a + \dfrac{R + jL\omega}{1 - LC\omega^2 - jRC\omega}$

The "stage gain," as it is called in amplifier design, or voltage across the tuned circuit is:

$$\frac{\text{External Impedance } x\mu}{\text{Total Impedance}} \text{ which is}$$

$$\frac{\dfrac{(R + jL\omega)\mu}{1 - LC\omega^2 + jRC\omega}}{R_a + \dfrac{R + jL\omega}{1 - LC\omega^2 + jRC\omega}}$$

Multiply top and bottom by $1 - LC\omega^2 + jRC\omega$ and then also divide the answer by $R + jL\omega$ to get current in the plate coil for this will give voltage across the grid coil when M is taken into account.

The plate coil current is then:

$$\frac{\mu}{R + jL\omega + R_a - R_aLC\omega^2 + jRR_aC\omega}$$

The voltage across the grid coil when this is open circuited is simply $jM\omega$ times this current, the voltage being caused by rate of change of current, and as the rate of change of a sine wave is a wave 90° ahead in phase the j must be in $jM\omega$ to give the phase advance.

The grid voltage is then:

$$\frac{jM\omega\mu}{R + jL\omega + R_a - R_aLC\omega^2 + jRR_aC\omega}$$

which must be equated to 1 as it was produced by 1 volt and so must *be* the 1 volt.

Multiply the denominator up and we have:

$$jM\omega\mu = R + jL\omega + R_a - R_aLC\omega^2 + jRR_aC\omega$$

CHAPTER XXXI

AERIALS

THE simplest aerial is perhaps the Hertz which was used in wireless sets sold as toys more than a quarter of a century ago, well before the valve was invented. It consisted of two horizontal pieces of wire soldered to two plates as in Fig. 160.

Leads from a spark coil went to *A* and *B*. The plates were charged + and − before the spark passed. When it did,

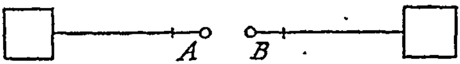


FIG. 160.—THE HERTZ AERIAL.

current flowed along the wire and circles of magnetic flux were generated round the wire. This is inductance, and as the two plates form a condenser (and even the two wires alone) the circuit was oscillatory. It generated damped oscillations of short wave length.

Later Marconi used a vertical aerial and when it is working in tune, i.e. its length adjusted to give the best results at a given frequency, its length is ONE QUARTER the wave length being sent or received. Voltage is high at the top and small at the bottom but considerable currents flow in at the bottom. There are none at the top. (See Fig. 161).

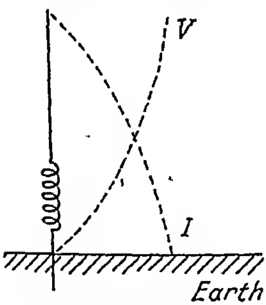


FIG. 161.—QUARTER WAVE AERIAL.

The coil *C* couples the aerial to the set. It is a case of a quarter cycle of a standing wave. Instead of the ground one can use another $\frac{1}{4}$-wave aerial giving a total length $\frac{\lambda}{2}$ as in Fig. 162.

A particular arrangement of masts holding aerials will tend to send more power out in one direction than in another. For

example, a plain vertical aerial behind a "live" one, will cause the region behind the dead one to be screened. The two aerials are placed $\frac{1}{4}$ wavelength apart.

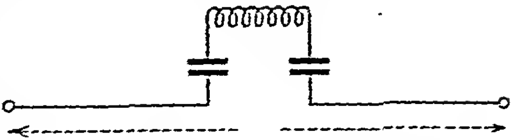


FIG. 162.—THE QUARTER WAVE AERIAL.

On Screening in Apparatus.

The effects causing interference are electrostatic and magnetic: two separate things.

In the first, high voltages (on a tag) cause interference by capacity currents to, say, the grid of a valve. Any metal screen, even tin-foil is quite good, the currents are small and cannot cause much pressure in the foil due to its resistance, since the currents are so very small because of the 10^{11} in the denominator of air capacity problems.

Screening against magnetic flux is different. The flux in a tuning coil is, however, kept back by an aluminium can because eddy currents in the can are out of phase with the coil currents 180°. It is low frequency power fluxes which are troublesome to screen.

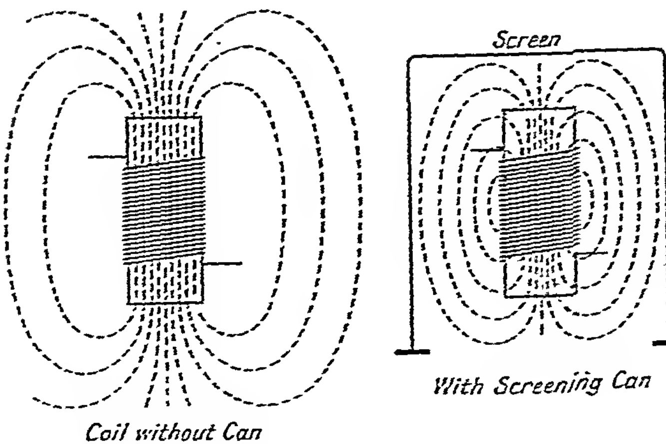


FIG. 163.—EFFECT OF SCREENING IN MAGNETIC FIELD.

CHAPTER XXXII

EXPLANATION OF LEAKY GRID DETECTOR CIRCUITS

THE all-important feature of this circuit is the condenser C put in series with the grid as in Fig. 108, charged by the flow of GRID CURRENT even when there is no radio signal applied to the grid. Fig. 107 which is the *vital curve* for this detector, shows a test on a valve grid with a D.C. micro-ammeter, and a whole volt of negative bias did not make the grid current zero. It reduced the flow to 1 microampere showing that there is 1μ amp. and 1 volt negative bias in this valve when a 1 megohm resistance is connected as the grid leak. The values must agree with Ohm's Law, and the 1μ amp. was measured. When the radio wave makes the grid more negative, less current flows to the grid. When less negative on the other half cycle more current flows. As it is a curve, the TWO HALVES OF THE CURRENT WAVE ARE UNEQUAL. This is what causes a charge to be left in the condenser after each complete wave of radio frequency. If the curve is assumed as a parabola, which it is very closely, and the equation contains a term ax^2, the x being grid voltage, then the "a" settles the amount of the charge on the condenser, as it settles the difference between the heights AB and AC in Fig. 109 which shows grid currents for 1 cycle of the radio wave. The B is one peak and C is the other.

The charge left on the condenser per cycle depends on the size of "A". One half of the wave puts current in and the other takes it out: but it is like putting fivepence in a money box and taking fourpence halfpenny out. As the working point alters when the accumulated charges (the half-pennies) on the condenser mount up, and act like a grid bias, the charge added per cycle remains the same unless the radio wave alters in amplitude which it does during modulation. Ignoring the modulation for the moment the average value of $\text{Sin}^2\,\theta$ is $\frac{1}{2}$ so when the x in ax^2 is $\text{Sin}\,\theta$ we have that the average of "$a\,\text{Sin}^2\theta$" is "$\frac{1}{2}\,a$" which is a charge current for 1 volt of radio wave applied to the grid.

There are other terms as well as x^2 in the equation to the curve and these will be considered later, but for the moment consider the modulation. Now consider detection of a modulated wave using this circuit.

As the wave gets bigger and smaller the precise way is shown by $V \sin \omega_o t\,(1 + M \cos \omega_p t)$. Here ω_o is the carrier and ω_p the speech. The factor M is the depth of modulation. What matters now is that the size of the radio wave is its voltage unmodulated, say V multiplied by a factor. The factor is : $(1 + M \cos \omega_p t)$.

Since the current per cycle of the radio wave depends on ax^2, it depends on the *Square* of the amplitude of the radio wave or on:

$$V^2 (1 + M \cos \omega t)^2.$$

Further, because 1 volt of carrier gives $\frac{a}{2}$ we have a current of

$$\frac{a}{2} V^2 (1 + M \cos \omega t)^2 \text{ amperes}$$

when the modulated wave is applied. Here the wave is supposed to be too small to run off the parabolic portion of the curve. The current is as follows when the square bracket is multiplied:

$$V^2 \left(\frac{a}{2} + Ma \cos \omega_p t + M^2 \frac{a}{2} \cos^2 \omega_p t\right)$$

Examine these terms one by one.

Here $\frac{a}{2}$ is a steady term and $MV^2 a \cos \omega_p t$ is a current of *Musical Frequency*: i.e the *Wanted Current*.

The $M^2 \frac{a}{2} \cos^2 \omega_p t$ is a double frequency or second harmonic.

This is why M ought to be small making M^2 smaller still and so negligible. One does not want big manufactured harmonics.

This means small depth of modulation at the transmitter.

Concentrate on the main term now.

The feed of musical CURRENT to the condenser is then:

MV^2a amperes showing that it is a *Square law detector*;

double V, the strength of signal and the musical current to the condenser charging it up is increased fourfold.

Lastly, let us consider the other terms of the equation to the Fig. 107 curve. It has a definite, simple slope or first differential, and so "more volts—more amps. to the grid" showing that the grid acts also like a resistance shunted across the grid leak as well as acting as a "charger" of the condenser due to its curved characteristic.

The value of this resistance is the slope of the grid current curve at the working point, and is about a megohm in the valve tested by the author. The problem is now solved.

Condenser Musical Voltage.

The circuit consists of a device, the grid, giving a charge current (MV^2a) to the condenser circuit. M is the depth of modulation, V the carrier voltage unmodulated and "a" depends on the curve of valve grid current, not on plate current. The charge and discharge circuit of the condenser consists of three parts:

(1) The condenser.
(2) Grid Leak.
(3) The equivalent resistance of the grid, i.e. slope of grid current curve.

These are all in parallel.

If the valve grid curve has a slope which makes it a resistance Rg at the working point and the grid leak is R, it is easy to see what voltage on the circuit in Fig. 109A will be built up by a current of V^2Ma amperes because 1 volt would give a current $C\omega$ through the condenser and $\frac{1}{R} + \frac{1}{Rg}$ amperes through the resistances together.

The total is $\sqrt{(C\omega^2) + \left(\frac{1}{R} + \frac{1}{Rg}\right)^2}$ amperes.

so for V^2Ma amperes the voltage is

$$\frac{V^2Ma}{\sqrt{(C\omega^2) + \left(\frac{1}{R} + \frac{1}{Rg}\right)^2}}$$

It is right to suppose that the condenser charge current is,

as it were, put in with a separate wire; for the diode charging action is independent of the working point when the curve is a parabola, for it depends on the second differential which is constant in a parabola and unvarying.

Frequency Response.

The formula shows that when the frequency of the audio wave is high, $C\omega$ becomes big and being down below, it makes the voltage small, so the high notes fall off. One way of saying this is that at high modulating frequencies the condenser has not time to discharge. Since the $C\omega$ and the current in the resistances are added as vectors at right angles or "T'eed on" the reduction is not marked until high frequencies in the music are reached.

Conclusion.

The musical voltage across the grid leak is the wanted music, and the explanation is complete. The plate circuit simply has an amplified copy of the grid voltage in it.

There is the high frequency pressure added to the musical voltage causing the total grid swing to be an addition curve as in Fig. 110 but there is no need to draw plate currents. What one does is to subtract the H.F. from Fig. 110 and get the musical current.

CHAPTER XXXIII

MAINS POWER SUPPLY UNITS

IT is possible to dispense with batteries entirely and draw current from D.C. or A.C. mains. There are then four problems.

(1) Currents for H.T. from Direct Current Mains.
(2) „ „ L.T. „ „ „ „
(3) Currents for H.T. from Alternating Current Mains.
(4) „ „ L.T. „ „ „ „

These will be considered in order. The current from D.C. mains is in reality a fluctuating current due to the dynamo commutator. A choke and, say, a 10 mf. condenser does good when connected as in Fig. 164.

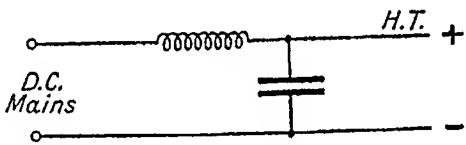


FIG. 164.—SMOOTHING IN D.C. MAINS.

When the L.T. is drawn from D.C. mains one uses indirectly heated valves with preferably a higher voltage than the usual 4 or 6 for heaters and with the increased voltage less current is needed.

All heaters may be put in series with a resistance to drop the voltage.

H.T. From A.C. Mains.

If A.C. mains are used it is first necessary to find a means of rectifying the current. The result is a pulsating D.C. and this is smoothed with a "Low Pass" filter consisting of condensers and chokes as described for D.C. smoothing. It is then ready for the set. Since a diode valve will allow a current to flow in the conventional direction of plate to cathode and not the other way, two diodes with a centre tapped transformer

In the co-axial cable, as in the wave guide, and indeed as in the two-wire line, when a *sine* wave oscillator is connected to one end, and when reflections from the other end are obviated, then a simple case of wave transmission takes place.

Attenuation.

At any particular place with a sine wave source voltage and current are sine waves too; just alternating currents. Generally these become weaker as they travel further from their source. This is called "Attenuation".

If, however, one takes not a particular *place* but a particular instant in *time*, there is a damped sine wave spread out along the cable. If it is at an instant when the input has reached maximum voltage, the voltage a little way along the cable has not yet reached a maximum. At telephone frequencies there is a phase change of so many degrees per mile. At higher frequencies there may be a complete cycle traversed in a few yards or even less.

CHAPTER XXXV

A TYPICAL HETERODYNE RECEIVER

THE theoretical circuit in Fig. 166 shows a typical superheterodyne receiver, of a fairly simple type. There is a frequency changer valve, a high frequency tetrode or pentode valve to amplify the I.F. currents, and a double diode, one side of which rectifies the I.F. currents to give the Low Frequency. This valve also has a triode section which amplifies the music before it goes to the output tetrode. The other section of the diode provides a voltage to give automatic volume control.

Aerial Circuit.

The aerial is untuned, and is connected to a coil *A* of a few turns; an arrangement known as "aperiodic". The coil *A* is tightly coupled by being wound on the same former as the tuning coil *T*, which is tuned by the variable condenser *C*.

The Oscillator.

This condenser has a smaller section *S* on the same shaft, which tunes the oscillator grid coil *G* generating a wave frequency of 465 kilocycles above the frequency to which the main tuning circuit, *T* and *C*, is tuned. This 465 kc. separation is constant for every position of the tuning condenser as the knob is turned, and is accomplished by correct shaping of the condenser vanes. The ·0001 μF. condenser and 50,000 ohm resistance provide a grid bias for the oscillator.

The incoming signal and the oscillator interact in this "Pentagrid" valve to give the intermediate frequency or I.F. in the plate circuit.

Notice the arrangement for giving a low voltage to the screen of this valve—two resistances in series. This feeds the screen of the next valve also.

The Intermediate Frequency.

This current goes to the primary coil of the first I.F. transformer and the secondary coil goes to the grid of the I.F.

amplifier valve. The plate of this tetrode or pentode goes to the primary coil of the 2nd I.F. transformer and the secondary coil of this goes to the diode section of the diode triode.

Each coil of the I.F. transformers is tuned by a separate small condenser adjustable—by a screw-driver—to 465 kc.

At the diode-triode valve the circuit becomes more complicated.

The Diode Detector.

The Intermediate Frequency currents generated in the secondary of the 2nd I.F. transformer are rectified by the

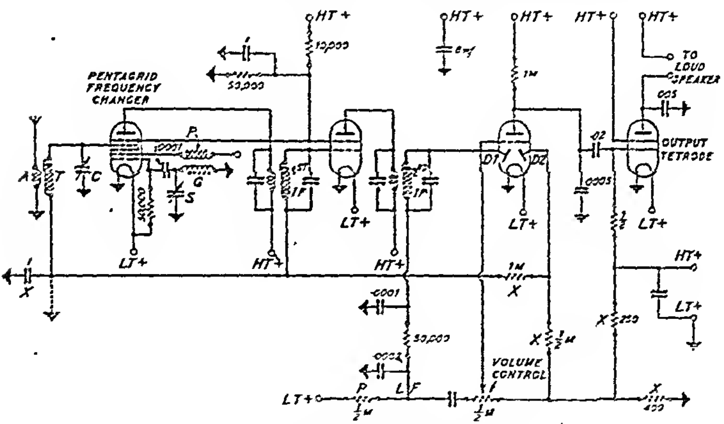


FIG. 166.—THEORETICAL DIAGRAM OF A BATTERY TYPE SUPER-HETERODYNE RECEIVER.

diode D1 and a steady current flows through the $\frac{1}{2}$ megohm leak *R*. The radio frequency current is smoothed out from this by the 50,000 ohm resistance and the condensers ·0001 and ·0002 μF. As the strength of the I.F. wave varies with the modulation of the original signal wave, the rectified current varies in strength so that music is obtained at the point marked L.F. This point feeds the volume control potentometer marked $\frac{1}{2}$ M. through the ·01 μF. condenser. The volume control feeds the grid of the triode section of the double diode triode.

This valve is resistance capacity coupled to the output triode by the ·02 μF. condenser. The additional ·0005 μF. condenser here helps still further to get rid of radio frequency current.

Automatic Volume Control.

Loud music is picked up by the second diode D2 because the volume control does not go to earth direct, but through a 400 ohm resistance. The result is to put a charge on the 0·1 μF. condenser at the left-hand side of the drawing and so give a negative bias to the frequency changer and to the I.F. amplifier, resulting in smaller amplification.

The efficiency of the circuit may be questioned, since 400 ohms is so low, and the A.V.C. circuit may be left out.

The simplified receiver, however, works well and is easy to construct and adjust. The following valves are suitable. (American numbers in the 1·4 volt range):

Frequency Changer	I A 7
Intermediate Frequency Amplifier	I N 5
Diode Triode	I H 5
Output Tetrode	I C 5

When using these valves and the simplified circuit, omit the components marked X.

Final Adjustment of the Receiver.

The small condensers which "trim" the I.F. transformers are tuned to receive the loudest possible music from some station of only moderate strength.

If it is found then that there is a "whistle" present, the entire turning of the four trimmers can often be altered altogether little by little, until they are in tune with each other but at a different frequency, so that the interfering station no longer makes an audible whistle. A little adjustment to the trimmers of the main and oscillator condensers completes the alignment. This method of adjustment is for the amateur who usually does not possess an oscillograph.

CHAPTER XXXVI

MAXWELL'S CURL EQUATIONS

IN dealing with electric waves there are two relations known as "Curls". They look simple to write, but mean a great deal. The two equations are:

$$\text{Curl } E = \dot{H} \text{ and Curl } H = \dot{E}.$$

In an electric wave there is always electric stress E. It is used by a cable maker who puts half an inch, say, of insulation between two conductors, and uses the cable for 6,000 volts. That means a stress of 12,000 volts per inch. The same idea is also used by the B.B.C. engineer who states that the "field strength" in a certain district due to his latest broadcasting station is so many millivolts per metre.

To grasp the idea, suppose we take a centimetre cube of air and consider it to have a metal sheet on each of two opposite faces. If a 1 volt battery be connected to these metal plates, then there is an electric stress in the space across the cube of 1 volt per centimetre. That is to say $E = 1$ in the space. If the plates were separated to two centimetres apart it would be $E = \frac{1}{2}$ and so on. This is the meaning of E, and the following table should make it clear. It is a question of the length of the lines of force between the two plates, oppositely charged.

Space between Plates	*Voltage Between Plates*	*Electric Stress "E"*
centimetres	volts	–
1	1	1
$\frac{1}{2}$	1	2
2	1	$\frac{1}{2}$
1	4	4
2	6	3

The importance of E is, that when it is there, the space is *charged* with a certain number of coulombs or ampere seconds.

For a given stress value the number of coulombs depends on the area of the metal plates: so many coulombs for each square centimetre of plate area. This is not current, but "*quantity*" of electricity. Moreover, when the stress is first applied and the Maxwell displacement is set up in the charged space, it is not due to a *flow* of electrons. Yet the astonishing thing is that when you vary the stress E and so vary the quantity of displacement—and so cause a displacement *current* in the space—this current has power to cause magnetic fluxes just like a flow of electrons in a wire.

Rate of Change.

This means that when we say:

$$\text{Curl } H = \dot{E}$$

we are talking not of the mere value of electric stress E, but of its rate of change $\dot{E}$; which means so many amperes across every square centimetre of the space where the stress exists.

This way of defining a "flux" of displacement current by means of a centimetre cube is much better than the usual sort of definition of a charged particle sending out radial lines of stress. It makes displacement current just like the centimetre cube used for resistances, and this is the way the units *ought* to be defined.

But to continue. The curl equation says much more than that we are talking of a changing stress $\dot{E}$. It says that $\dot{E}$ equals, or causes, a magnetic force H, in the same way that electronic current in a wire causes magnetic force in the space surrounding the wire. The curl equation however is more exact. It tells the value of the electric current $\dot{E}$ *exactly* at any *spot* in terms of the magnetic field *there present*. It is $\dot{E} = \text{Curl } H$, with emphasis on the word "Curl".

Meaning of "Curl".

What does curl mean? It is the idea of going round a closed loop. Take a long straight wire carrying a current and take a circle round it where the strength of the magnetic force caused by the current is 10. That is to say $H = 10$ on that circle. Suppose the circumference of the circle is 4 centimetres: then the line integral round the circle of H is $4 \times 10 = 40$. This 40 measures the current in the wire.

Suppose we take a field of electric stress as indicated diagrammatically in Fig. 167

The field is imagined all in parallel downward lines, but stronger as we go from left to right as shown by the numbers 10, 20, 30, etc. These numbers are volts per cm., the centimetre being measured along the lines. Take a square $A\ B\ C\ D$, and form a line integral of electric force E round it. There is no electric stress along $A\ B$ for the force is downwards. Along $B\ C$ it is of value 20 down.

The curl square is supposed to have sides of 1 cm. Thus $E \times l$ for the side $B\ C$ is $20 \times 1 = 20$ volts. The line $C\ D$ contributes nothing, but $D\ A$ contributes a downward voltage of $10 \times 1 = 10$ volts. There are then, going round the loop two opposing voltages 20 and 10. By subtraction the loop voltage now becomes 10. What we are saying is that $10 = \frac{\dot{B}}{10^8}$ so this line integral of E round the square $A\ B\ C\ D$ measures the $\dot{B}$ or changing magnetic flux in or through the loop.

Flux Change.

Notice that any changing flux in a loop is dependent upon the lines of electric force· whether as you cross the lines of electric force at right angles—in this case crossing a set of vertical lines from left to right—you find *variation* in the strength of the electric field. The lines go 10, 20, 30 and not 20, 20, 20. If you find variation *across* the square there is flux change *through* it.

If the field of electric force is vertical the proper symbol is E_y. The subscript y means in a "y" direction. But the variation as you go in a horizontal direction is $\frac{dE_y}{dx}$: so with a vertical field this is the Curl of E and measures magnetic flux change through the square.

There are three more things to be considered. The first is that the force E may not go in such a simple way as 10, 20, 30 for each centimetre, but at any particular place it is possible to imagine a small square, and to measure $\frac{dE_y}{dx}$ across the square.

Secondly, the force may not be vertical. If it were horizontal it would be $\frac{dE_x}{dy}$ meaning the change in strength of horizontal lines of force Ex as we cross them at right angles by going in the y direction.

Thirdly, if you have both vertical and horizontal force E_y and E_x and if these forces get stronger as both x and y increase, then they both oppose each other when we consider their contribution to the curl. So the total Curl is not the addition of

$$\frac{dE_x}{dy} + \frac{dE_y}{dx} \text{ but}$$

$$\text{Curl } E = \frac{dE_x}{dy} - \frac{dE_y}{dx}$$

An Analogy for Curl.

Suppose a flat square board to be dropped into a stream. Will it turn round and round? It will if the current is faster on one side of the stream than on the other. You have then a stream flowing one way. To see if there is any variation in the rate of flow you cross it from side to side. That is another direction. If there is a faster flow on one side than on the other, the board will turn or spin about a vertical axis. That is the third direction, or axis, involved in Curl.

Perhaps the best analogy for Curl is a dart and dartboard. In taking a Curl of E, regard the dart as a changing magnetic flux $\dot{B}$ or, since B and H are proportional in air and most materials, the dart is $\dot{H}$. The E lines flow in the plane of the dartboard, so Curl E relates a *time* variation of magnetic force H with a space variation of E the electric force.

The Curl of H the Magnetic Force:

Electric current always causes Magnetic Flux and Maxwell's displacement current caused by variation of electric force E produces a magnetic force just as surely as a flow of electrons in a wire causes magnetic force round that wire.

Here then the dart is $\dot{E}$ for if it is air we are considering, the permittivity of air is 1, and $\dot{E}$ means a current. If

however it was an insulator with specific inductive capacity 6, it would be Current $= 6\dot{E}$. In general it is $\epsilon_0\dot{E}$ where ϵ_0 is specific inductive capacity.

Usually, radio waves are in air so it is just $\dot{E}$, though if one wants current in amperes there is a 10″ factor and also a 4π.

Since $\dot{E}$ is a current it causes magnetic force H. We take a Curl of H in the dartboard to determine the strength of Maxwell's displacement current $\dot{E}$.

The actual forming of the Curl, its expression or writing in differential calculus symbols depends on the co-ordinates used. If it is just plain x and y co-ordinates, then curl is written $\frac{dH_y}{dx} - \frac{dH_x}{dy}$ If however the problem is one involving a circle or cylinder in which we wish to put the dartboard for taking the curl, cylindrical polar co-ordinates are better. These are, one, the z axis along the cylinder; one along a radius r; and at any point one axis along a tangent to a circle, an angular co-ordinate θ. Then the dartboard is circular and not square, which gives the sectional shape shown in Fig. 168.

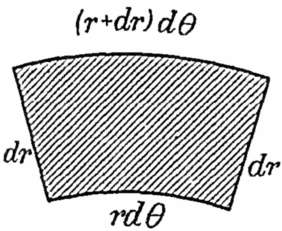


FIG 168

Suppose a wave is travelling in a hollow circular pipe and one suspects lines of electric stress in circles in the pipe, then there is no component of E along a radius, so the sides of length dr of the dartboard contribute nothing to Curl E.

To take a curl of E then in this simple case, E must be multiplied by the arc length $rd\theta$, and an E which is different by an amount dE, *i.e.* $E. + dE$ must be multiplied by the length of arc $(r + dr)$ $d\theta$, to form the line integral which is Curl.

These oppose each other round the loop, so their subtraction: $(E + dE)$ $(r + dr)$ $d\theta - Erd\theta$, gives the Curl of E, or at least the total voltage. It is :

$$Edrd\theta + dErd\theta + dEdrd\theta$$

This voltage is caused by a dart of flux change through

the dartboard. If the flux density is B the flux is $Brd\theta dr$ for $rd\theta dr$ is the area of the dartboard.

Thus:

$$Edrd\theta + dErd\theta + dEdrd\theta = Brd\theta dr.$$

We can always write dE as $\frac{dE}{dr}\,dr$. Then we can divide by $drd\theta$ and we have

$$E + r\frac{dE}{dr} + \frac{dE}{dr}\,dr = r\dot{B}$$

We say $\dot{B}$ because it is flux *change* that causes voltage As the curl square is made minute, $\frac{dE}{dr}\,dr$ disappears to zero for dr shrinks to O. So $E + r\frac{dE}{dr} = r\dot{B}$.

But what is $E + \frac{rdE}{dr}$?

It is $\frac{d(Er)}{dr}$ so we may write $\frac{d(rE)}{dr} = r\dot{B}$ or better still:

$$\dot{B} = \frac{1}{r}\frac{d(rE)}{dr}$$

which is Curl in polar co-ordinates for the simple but important case where the force E to be curled is in circles.

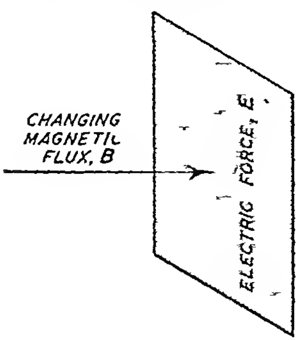


FIG 169 —CURL $E = \dot{B}$ or $\dot{H}$. Showing how a time variation of H along a dart is related to E in the board

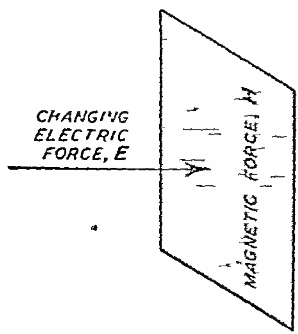


FIG 170 —CURL $H = \dot{E}$ Showing how a time variation of E along a dart is related to H in the board

The Use of Curl Equations.

The above equation may not be much use as it stands alone; but as one small simple equation like the small simple equation $x = 2y$ in a problem which begins "A father's age is twice that of the son," this Curl equation may be combined with others and the complete solution to a problem found.

We do not wish to go further, here, but if the reader should say "I understand the value and use of $\dot{B} = \frac{1}{r}\frac{d(rE)}{dr}$ but why call it Curl E?" then surely the answer would be, anyone seeing $\dot{B} = \frac{1}{r}\frac{d(rE)}{dr}$ would naturally ask where it came from; and the answer would be that it springs from the generation of a voltage in or *round* a loop by a changing magnetic flux *through* the loop; an idea of such supreme importance when applied to minute loops as to deserve the special name of "Curl".

The whole matter may be summed up by saying that the student knows that a changing flux through a loop causes a voltage round the loop. Make the loop small and this defines the flux density through the minute loop and therefore *at a point.*

So much for Curl E.

As regards Curl H, every student knows a current in a wire causes flux round the wire. It is a simple step to say that a current may be a flow of electrons or it may be ether displacement caused by changing electric force $\dot{E}$.

Many of us may have felt that Maxwell's Curl Equations were beyond us. They are not. It is simply a case of grasping his idea of a displacement current in the ether being like a current of electrons in a wire as far as the magnetic action goes, and asking what magnetic fields such currents must cause.

The use of calculus is not very difficult here, once one gets used to it. It is the polar co-ordinates that make it hard.

CHAPTER XXXVII

WAVE GUIDES

YEARS ago Lord Rayleigh, who was the great authority on sound, showed that electric waves could travel along the inside of hollow tubes without much weakening, if for a given tube diameter the frequency was high enough. The hollow tube is called a wave guide. In wave guides it is necessary to study the patterns of the fluxes (both magnetic and electric) in the space in the guide. Without going more fully into the mathematics of the subject one can only get a general idea of what is happening, but the knowledge gained can be very useful.

The Fluxes Concerned

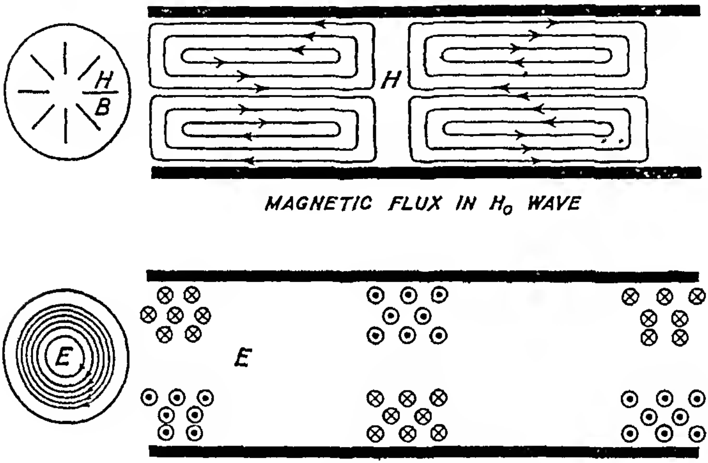
Faraday's original electrostatic experiments are the beginning of the subject. It is a case of the charge and discharge of the capacity of space. Consider what happens when a "plate" condenser is charged. The space between the plates becomes charged. Maxwell's displacement current flows in the space, and electrons flow in the wires leading to the condenser. The amount of flow in the wires is equal to that across the space.

The ether displacement current is one of the things which we have to consider in studying waves, because these currents cause the magnetic flux of the wave. This magnetic flux by its motion causes the voltage (the electric force or E of the wave) with which we began. The two fluxes then are electric and magnetic flux usually denoted by E and B. Since for air with permeability we have $B = H$ it follows that E and H are the quantities concerned.

Round Guides.

In many ways the round guide is easier to follow. It is not easier in the mathematics, for the use of the equation $\frac{1}{r}\frac{d(rE)}{dr}$ at once brings a Bessel function into the mathematics, but if one does not need exact calculation, then the round

guide is easier. Suppose a bunch of lines of magnetic flux to flow along the tube as in Fig. 171. How could these be supported? Naturally, one would say, by circulatory currents. Since current in space consists of increasing (or else decreasing) electric stress in the space, the lines of electric force must be in circles. This is called a Magnetic Wave, since magnetic force goes along the tube. Fig. 172 shows the circulatory current path with this wave.



ELECTRIC FLUX IN H_0 WAVE

FIG 171—THE MAGNETIC AND ELECTRIC FLUXES IN A MAGNETIC WAVE IN A ROUND GUIDE

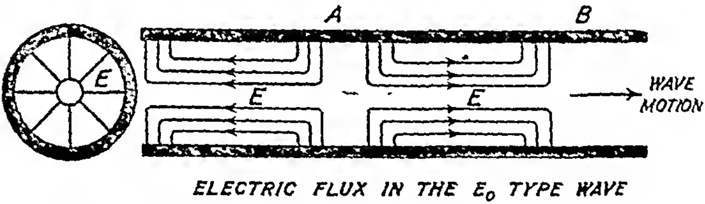
A Magnetic Wave.

Since it is alternating currents of very high frequency that we are dealing with, the bundle of lines of magnetic flux is followed by a bundle of lines having the reverse direction. The flux at the end of the bundle "fans out" and returns along the inside edge of the tube. Each bundle is one half cycle of the sine wave. The electric currents are circulatory as said, and the strongest current is to be found round the middle of a bundle of lines of H or of flux B. Since, however, the currents are rates of change of voltage or of force E, it follows that the strongest currents are where zero voltage is!

FIG. 172.—THE ETHER DISPLACEMENT CURRENT IN WHAT IS CALLED A MAGNETIC WAVE, OR AN "H" WAVE.

This is because we are dealing with sine waves and the greatest rate of change or slope of a sine wave is at the zero. As we usually mark electric force E on the drawings, the greatest concentration of circles of electric force E should be at the ends of the bundles of magnetic flux, which is what the drawings show. This wave is called an H_0 wave. The letter H signifies magnetic force along the tube and the subscript "o" signifies no diametral nodes as one goes round in a circle. With this wave, the flux round any circle is uniform.

As stated, if we go along the tube at any instant of time we observe a sine wave of flux or of electric force. Along the axis of the tube there is strong magnetic flux at every maximum. That is at any given instant. But the whole wave,



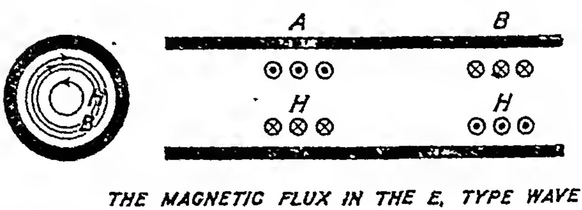


FIG. 173.—THE ELECTRIC AND MAGNETIC FLUXES IN AN ELECTRIC WIRE IN A ROUND GUIDE.

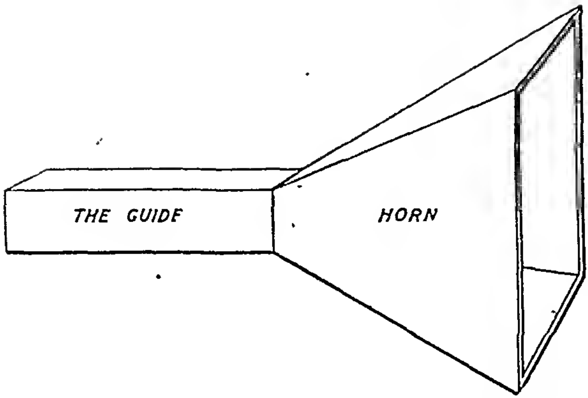


FIG. 174.—A HORN ON THE END OF A WAVE GUIDE FOR RADIATING ENERGY.

the whole "state of things" flies along at a steady great velocity. If then we stand at one spot and let the wave go flying by, at that spot we have alternating electric force, alternating with time just as in all alternating current phenomena.

Rayleigh's Law.

Indeed it is a law of nature that if you put a sine wave oscillator anywhere, voltages or currents caused by it anywhere else must be sine wave voltages or currents of the same frequency.

An Electric Wave or E_0 Wave in a Round Guide.

With this type of wave, it is electric force, not magnetic force, that flows along the guide, and there is a difference in the shapes of the loops. These loops of electric force seize on to the metal walls of the tube; and, if there is a displacement *forward* along the tube, there is an electronic current in the tube *backwards* to complete the circuit. See Fig. 173.

In the metal there is the phenomenon of "skin effect", the electric current flows on the surface—the inside surface only—of the tube.

The magnetic flux like the circles of flux round a wire carrying a current is in circles here; circles round the bundle of lines of displacement current along the guide.

Attenuation of Waves.

As the waves travel there is some weakening due to losses. In the case of the electric or E wave it is easy to see that the resistance of the wave guide to the return current through it (ohmic resistance made greater by skin effect) must cause a loss. Yet over and above this, the waves suffer great weakening or attenuation if the frequency is *below* a certain critical value depending on the diameter of the pipe.

As the frequency is *raised*, skin effect becomes more pronounced.

The tube carries the main current in the case of the E wave, and this is like the current in the conductor of a co-axial cable.

In the case of the magnetic H wave however, the main current is in air as in Fig. 172, so skin effect cannot make it produce a greater loss.

As the frequency is raised without limit, the attenuation rises in the end, in the case of the E wave; but falls and falls away in the case of the H wave.

For this reason the H wave should have an important future. It is a matter of the greatest interest to the telephone engineer.

Rectangular Guides.

Mathematically these are easier to follow, for the flux distribution over the cross section of the guide, like the vibration of a plate in the Lissajous figure experiment on sounds, is a simple sine wave and not a Bessel function. These guides are excellent for short runs, but there is nothing like the H_0 wave in the round guide with the wonderful fall in attenuation as frequency rises.

CHAPTER XXXVIII

NEGATIVE RESISTANCE AND NEGATIVE INDUCTANCE

IN the last few years, certain substances have come into use in electrical engineering called *negative resistances*.

The most perfect example of a true negative resistance would be a simple series dynamo driven by an engine, and having "air" instead of iron for its construction material; shall we say wood, instead of iron to be very practical. Then if any current flows it will cause a magnetic field and since it is being driven by an engine a voltage will be produced which acts in a direction *helping the current to flow*. This is the reverse or negative of the case in an ordinary resistance in which voltage is needed to push current through a resistance. So a negative resistance is a generator. The graph of current and voltage in each case is shown in Fig. 175.

Dynatron and Transitron Circuits.

For telephone and other communication work a material is used which draws a steady current like a valve. Indeed two valve circuits, the "Dynatron" and the "Transitron" circuits give a negative resistance effect.

What matters is that, though there is a steady drain on the battery, the device takes *less* current when the voltage is

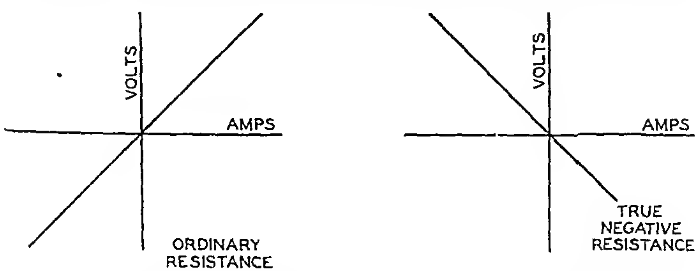


FIG 175 —VOLTAGE AND CURRENT IN ORDINARY AND IN "NEGATIVE" RESISTANCES

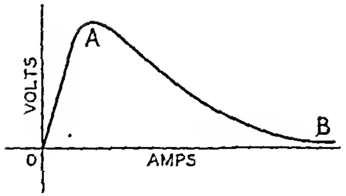


FIG. 176.—GRAPH OF SUBSTANCE HAVING "DYNAMIC" NEGATIVE RESISTANCE.

increased a little and *more* current when the voltage drops a little.

Germanium.

One such material is made from Germanium. The characteristic shown on a graph is given in Fig. 176.

The substance would act like an ordinary resistance for small currents but for larger currents if the large current varies, there is a negative resistance effect as regards the variation. The substance absorbs energy but by absorbing less current at the right moment, energy is added to the circuit from the battery. There is a unit made up with a little plate of the element Germanium about one-eighth of an inch square, having a light metal contact pressing on it.

If a suitable negative resistance element were found, telephone lines could have these devices at intervals along the line. In other words a line may be "loaded" with it, and the transmission loss, or "attenuation", as it is called, could be reduced to zero. That would be a great advance in telephone engineering.

If one considers how much mathematics owes to the use of negative quantities it is plain that great extension of technique will follow by the use of negative resistance in electrical work. One use is to make negative inductance.

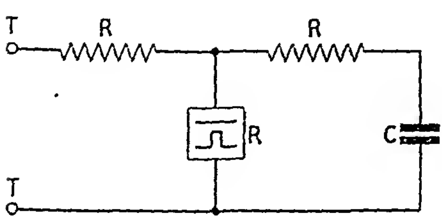


FIG 177.—NEGATIVE INDUCTANCE CIRCUIT

NEGATIVE INDUCTANCE

Suppose a circuit to be made up with two ordinary resistances, one negative resistance and a condenser as shown in Fig. 177. The negative resistance must have a battery feed which is not shown in Fig. 177.

The impedance at the terminals TT, at any frequency f may be calculated by the j notation thus. Let $\omega = 2\pi f$ as usual. The impedance of the condenser is $\frac{1}{jc\omega}$ as usual. If the three resistances are equal in size but in value R, R and minus R we put R in series with C as $R + \frac{1}{jc\omega}$.

We then put minus R in parallel thus: $$\frac{-R\left(R + \frac{1}{jc\omega}\right)}{-R + R + \frac{1}{jc\omega}}$$

by the $\frac{SUM}{PRODUCT}$ rule. Work it out and add the left hand R and it is $R - R^2jc\omega - R$ which is $-jR^2C$. This means that a value of $R = 1000$ ohms and a condenser of $2\mu F$ would give $-j2\omega$, at the terminals T.T.

Without the negative sign, $2j\omega$ would be the impedance due to two henrys.

A negative inductance means a leading current *like* a condenser *but* impedance rising with frequency not falling as in a condenser. The use of these must surely lead to an extension of technique.

CHAPTER XXXIX

PICTORIAL RADIOLOCATION

By sending a beam of rays from a transmitter in an aeroplane down to the ground, and by measuring the power of the reflection from the ground, using this to control the brightness of the beam in a cathode ray oscillograph, one can obtain a picture of the country below the plane, even if this is obscured by fog.

The technique is as follows. The beam is shone on every part of the ground in turn as in television. The "spot" is swept over the ground rapidly to cover the whole area again and again. The spot of light on the cathode ray screen formed by the electron beam is made to move in synchronism with the transmitted beam sweeping over the ground.

When the ground sends back a strong reflection, the oscillograph shows a bright patch. Thus a clear outline, indeed more than an outline of the ground features, appears on the screen.

Practical Use of Pictorial Radiolocation.

This should make flying much safer, for accidents in civil flying seem to happen at times of bad visibility.

The technique is a combination of television and the "simpler" type of radiolocation where a beam is sent up into the sky and if a plane is there, the reflected wave shows its presence. An absence of any reflection means an absence of any aircraft in the vicinity (see Fig. 178).

The waves are sent out in short trains or impulses lasting only one millionth of a second.

There are a thousand pulses to a second.

The wave is sent out by wave guide to the receiver also, and the time difference between the pulse going along the wave guide and the pulse reflected from the sky shows how far the aeroplane is away.

The receiving aerial is very directional. This helps to locate the plane exactly.

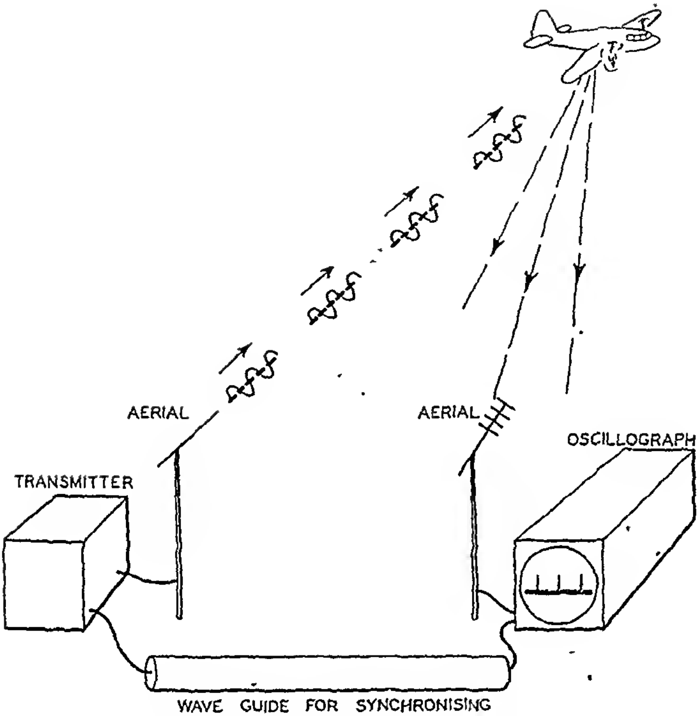


FIG. 178.—"SIMPLE" RADIOLOCATION.

These devices may yet be of good service in shipping. At the moment of writing, a big navigational aid scheme is being constructed at Liverpool for Mersey shipping.

In radiolocation, centimetre waves are used. One advantage is that a small aerial even will radiate a great deal of power.

Another advantage is that the beam is more like a beam of light in casting shadows. A long wave will "go round" an object but a short wave gives a shadow effect like light.

The Magnetron.

The use of such short waves involved the making of special valves. A "Magnetron" valve was invented at Birmingham

University capable of giving out several kilowatts, although its size was reasonably small. A magnetron valve is one which is placed in the field of a powerful magnet. The electrons in coming off the filament tend to cut the lines of the magnetic field at right angles, just as the current in an electric motor armature makes the conductors move at right angles to the magnetic lines of flux from the field.

The electrons describe curved paths round the straight wire filament and may return to the filament, or else describe a bigger path and hit the plate which surrounds the filament. In the Birmingham magnetron, the plate has a number of hollow little chambers or "resonators".

Every electron gives off an electrostatic field by virtue of its very existence. As an electron moves past the hollow resonator it sends lines of electric flux into the chamber, like a person dressed in white on a sunny day may illuminate a dark cave somewhat, just by walking past the mouth of the cave.

In order to carry a short wave or very high frequency current across a field, which is necessary in the earlier radiolocation technique, where a wave is shot into the sky to "see" if there is a plane about, wires are not much good. Too much energy radiates from the wires. That is why hollow metal pipes or wave guides are used.

It will be appreciated that in this simple radiolocation, separate pulses of short duration are sent into the sky. The pulse only lasts a millionth of a second, and so the valve has a good "rest" before the next pulse. Under this condition a small valve may momentarily send out a great deal of power.

The development of radiolocation from this simpler form to the later pictorial form where a map is drawn on the oscillograph screen, has been very rapid.

CHAPTER XL

EXPERIMENTS AND DEMONSTRATIONS

THE following experiments will be found to be particularly useful for demonstration purposes. Those which have not been fully described in the previous chapters are described more fully here.

In making up circuits, such as detector and modulator circuits, it is a great help to have a suitable A.C. bridge for measuring the inductances of coils. This will save much trial and error. Only the more difficult experiments are described here.

(1) Vector addition of Voltages in A.C. circuits.

(2) Diode, Triode, Tetrode, Pentode and Octode Characteristic Curves. The octode is described here, the others can be set up as described previously.

(3) Meissner, Hartley, Colpitts and Tuned Grid Tuned Plate oscillators. The Double Valve oscillator may be included. The oscillators are fairly straightforward.

(4) Leaky Grid and Anode Bend detection.

(5) A Triode as an amplifier of A.C.

(6) Grid Modulation, Choke Modulation and Octode Modulation.

(7) Low Pass Filter and Fourier Series.

(8) Band Pass Filter.

(9) Series Resonance.

(10) Parallel Resonance.

(11) Heterodyne Principle.

(12) Transients on Various Circuits.

(13) Lecher Wires.

(14) Frequency Doubler.

(15) Quality of Circuits.

(16) Multivibrator.

(17) Mains Rectifier and Filter Circuit.

These twenty or so experiments form a useful set for laboratory and demonstration work. In general, demonstrations should be simple to follow. If a complicated circuit

such as a square wave generator is used one can explain what it does, i.e. generates a square wave, without going into its action. Such circuits as detectors and oscillators are found fully described under the various descriptions of their working. Those which have not been given are now mentioned with a few details to enable them to be made up easily.

Vector Addition of Voltages.

An audio oscillator is connected to a circuit consisting of a resistance box in series with a variable condenser. This may be fractions of 1 mf. or 2 mf., such as ·1, ·2, ·5, 1 and so on. Even one condenser would do. Connect the centre point to the earth of a double beam oscillograph and put the voltage on the condenser on one beam and that on the resistance on the other beam as shown in Fig. 179.

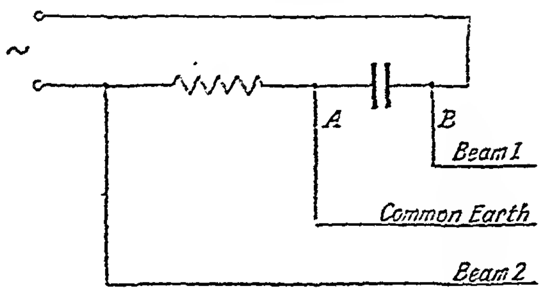


FIG. 179.—VECTOR ADDITION OF VOLTAGES.

Make the two voltages equal by alteration of resistance. Note the 90° phase difference. Change wires *A* and *B* about, to measure total voltage across the condenser and resistance (beam 2) and note by counting squares on the oscillograph that it is root two times either voltage component. Change the resistance for a good inductance like a telephone loading coil and see resonance effects.

Octode Characteristic Curves.

The valve is set up as in Fig. 180. The curves are shown in Fig. 181.

Fix the bias voltage on grid 1 first at *O* and plot plate

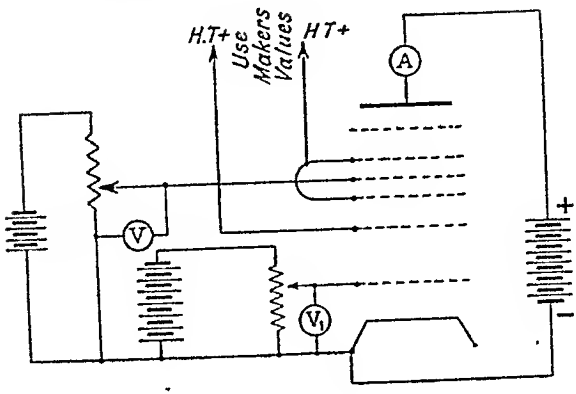


FIG. 180.—CIRCUIT FOR TAKING OCTODE CHARACTERISTICS.

current against voltage V on Grid 4. Alter the voltage on G_1 to say − 2 volts and plot a new curve between voltage on G_4 and anode current. Calculate the change of slope g for one volt change of voltage on grid 1. If the straight parts of the characteristics all meet (if produced) in one point and if the distance AB on the y axis for, say, 2 volts change on grid one, equals BC for another two volts change then since g the slope is tan θ the change in tan θ is the change AB divided by the common base or BC divided by the same base. So, with these conditions, a "focus" for all the lines, and AB = BC and so on, we have:

g is proportional to VG_1.

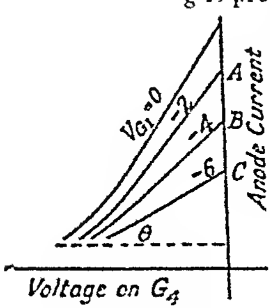


FIG. 181.
OCTODE CHARACTERISTICS.

Since plate current in a triode is proportional to g times the voltage on the triode grid which is VG_4 in this case we have that:

Plate current is proportional to V_{G_1} times V_{G_4}.

There are other terms in the plate current but this is the important one; when the octode is used as a modulator or as a frequency changer.

The circuit in Fig. 180 shows

how to make an octode give the usual text-book picture of a modulated wave, one replaces the grid batteries by H.F. and L.F. oscillators.

The Double Valve Oscillator.

Two valves are resistance capacity coupled. Usually little or no amplification is needed in one valve. (See Fig. 182.)

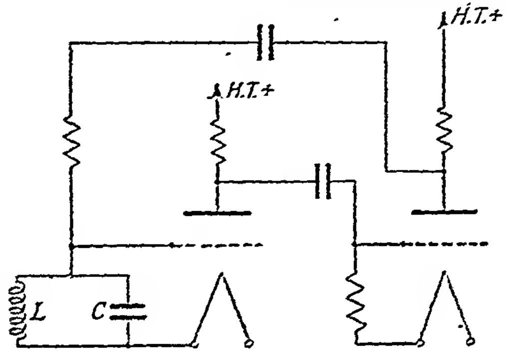


FIG. 182.—DOUBLE VALVE OSCILLATOR.

The condenser C is the tuning condenser, and the other two merely coupling condensers.

Low Pass Filter and Fourier Series.

If the square wave generator is fed to a Low Pass Filter the harmonics can all be cleared, and a sine wave results. (See Fig. 183.)

If the filter is set to cut off all but the fundamental and the

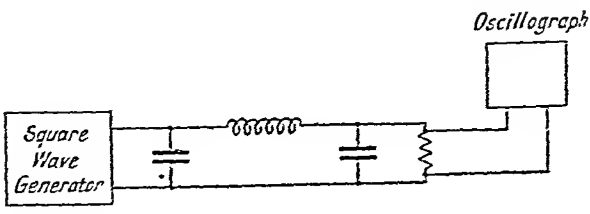


FIG. 183.—EXPERIMENT ON HARMONICS USING A LOW PASS FILTER.

third harmonic, these will be left and a wave with an added third will be seen on the oscillograph.

The frequency at which the square wave generator should be run depends on the size of filter coil available. About 200 c/s is right for a 120 millihenry coil.

The Tuned Transformer Band Pass Filter.

This experiment is hard to make successful until one hits on about the right components. Two little frame aerials of

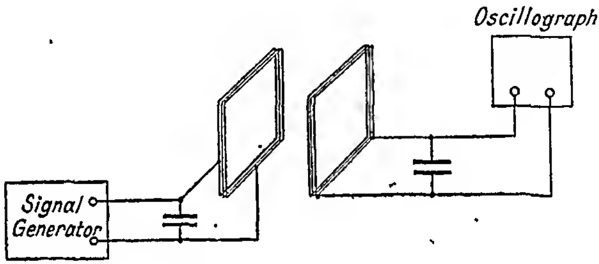


FIG. 184.—COMPONENTS OF TUNED TRANSFORMER BAND PASS FILTER.

about 8 or 9 turns each and about 15 inches square are sı able for use with ·0005 variable condensers. Then the us type of signal generator can be used.

The coils are placed about four feet apart, and tuned to give the biggest "ribbon" on the oscillograph which ought to be one with two amplifier stages in. The two circuits will then be tuned to the same frequency.

One can plot a curve between frequency and output voltage, i.e. width of ribbon, and when the coils are close together a "double hump" curve will be obtained which is what is aimed at in a superhet *IF* filter.

A valve voltmeter will do instead of the oscillograph. A high resistance in one lead between the signal generator and the tuned circuit takes the place of a valve and provides impedance. It should be 200,000 ohms or so. Then the current is fairly constant as in a high frequency valve used to feed the *IF* transformer.

Series Resonance.

This experiment is best done at audio frequency with a telephone loading coil or else at radio frequency. (Fig. 185.)

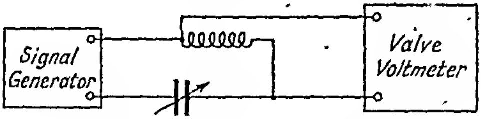


FIG. 185.—SERIES RESONANCE.

Ordinary broadcast coils are suitable and the usual size for medium waves is about 50 turns on a 2 in. diam. former, about one-sixth millihenry and the usual ·0005 mf. condenser. One alters the frequency of the generator and measures voltage. A valve voltmeter of as low an impedance as 10,000 ohms even gives good results.

Parallel Resonance.

This is best done with a tetrode as it is then part of a receiver circuit. (See Fig. 186.)

This shows a rise of voltage round resonance. The same

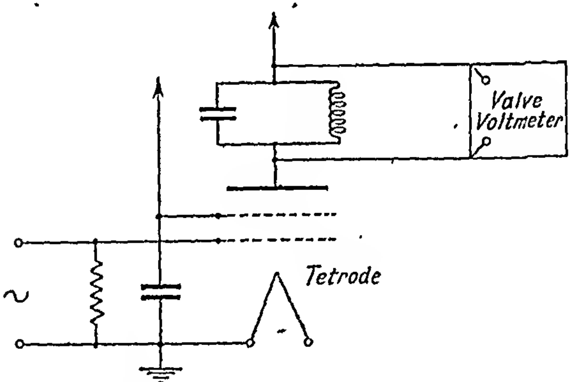


FIG. 186.—PARALLEL RESONANCE.

components are used as for series resonance curves. The tetrode impedance makes current independent of the frequency.

If one really wants to show a current dip one may dispense with the valve and put, say, 100 ohms in between the circuit and the signal generator. This acts as a "shunt" if the oscillograph is put across it, and turns that instrument into an ammeter.

The Heterodyne Principle.

The best way to show "beats" is to use two signal generators, one plain H.F. and one which can be modulated or not at will. They may not be equal, so a resistance box is shunted across each to vary the voltage. The beats will be seen when the two radio waves are given (See Fig. 187) about the same

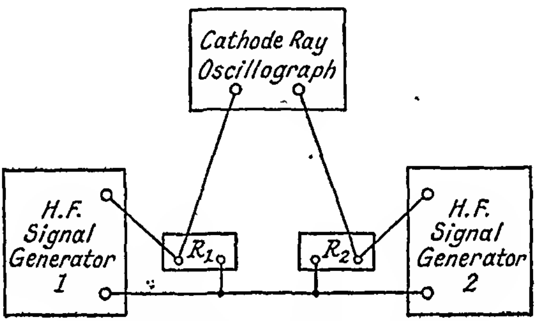


FIG. 187.—VISIBLE PRODUCTION OF BEATS.

frequency. They may if very close in frequency lock and form one wave.

If a modulated wave is used for one generator, one can see how the modulation affects the beats which show what the wave was like in the old type of superhet where two waves were added, before detection.

Circuit Transients.

The square wave oscillator gives a ready means of showing the transient currents which flow in circuits when a D.C. voltage is switched on. This current transient as Heaviside showed is fundamental. Six special cases are as follows (See Fig. 188.)

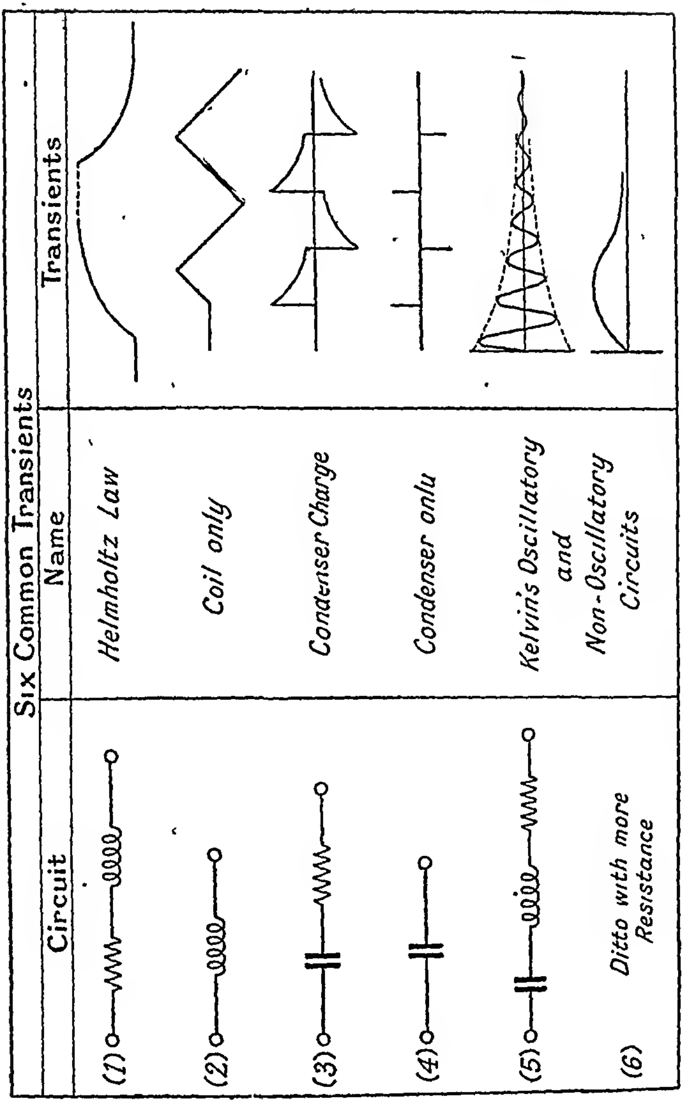


FIG. 188.—SIX COMMON TRANSIENTS.

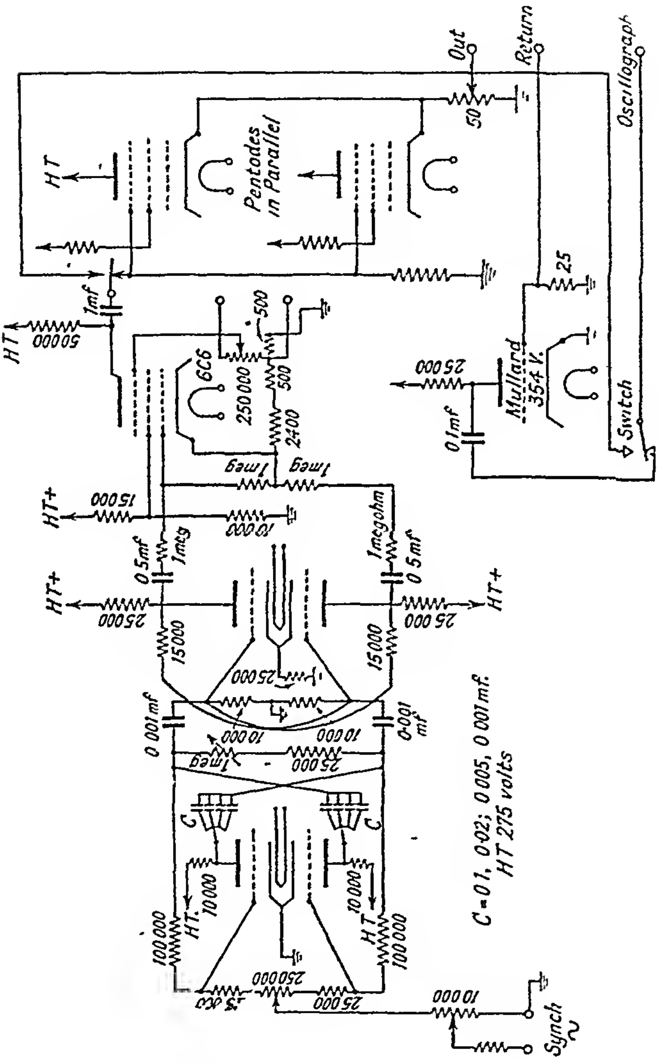


FIG 189.—SQUARE WAVE GENERATOR

(1) Helmholtz Law.
Use a coil and some 30 ohms in series.
(2) The coil with negligible resistance.
(3) Charge of a condenser through a resistance.
Use about 10,000 ohms and ·1 mf.
(4) The Condenser only.
Cut nearly all resistance out.
(5) Oscillatory Circuit.
Put the oscillograph across coil. Vary resistance.
(6) Coil condenser and resistance as for oscillation but too highly damped; no oscillation.

Any good inductance such as a telephone loading coil is excellent for the inductance and a fraction of 1 mf. and a decade resistance box complete the circuit to be tested.

The square wave generator may be run at about 200 to 300 c/s with a coil of about 120 millihenries. The multivibrator is a remarkably steady circuit and the picture very steady. The square wave circuit is given here. (See Fig. 189.)

Lecher Wires.

These may be 4 inches apart and 20 feet long for waves of about 3 metres long. The oscillator circuit is shown in Fig. 190 and consists of an oscillating "circuit" with the inter-electrode capacity of the valve as *C* and the single loop of the copper rods as *L*.

The chokes are about ten turns of wire round a pencil and the bridge condenser about ·0001 to ·002.

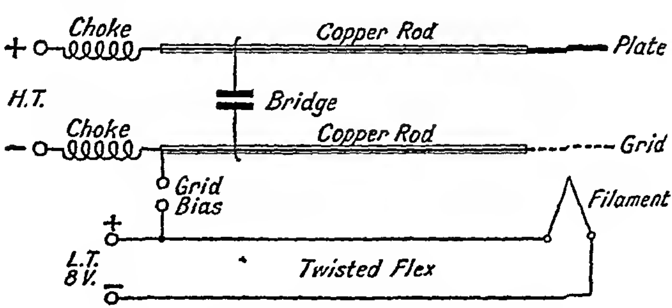


FIG. 190.—OSCILLATOR FOR 2 TO 3 METRES

The coupling to the lecher wires is a single loop of wire round the valve itself.

Quality of Tuned Circuits.

If in the experiment on the case of resonance of coil and condenser in parallel, an extra resistance is put in, one can find the total resistance of the tuned circuit. Suppose 5 ohms reduces the valve voltmeter deflection to half what it was, that means that there is half the impedance, so $\frac{L}{CR}$ is half, showing that R has been doubled. Hence if 5 ohms has been added, the tuned circuit resistance was 5 ohms to begin with.

The Multivibrator.

This circuit is of great laboratory use and also forms the basis of the modern oscillograph Time Base Circuit for high frequency use. The circuit is that shown in the first valve: the first double triode in the square wave generator on Fig. 189.

When one grid goes negative, the valve draws little current, making that plate positive. This puts positive pressure

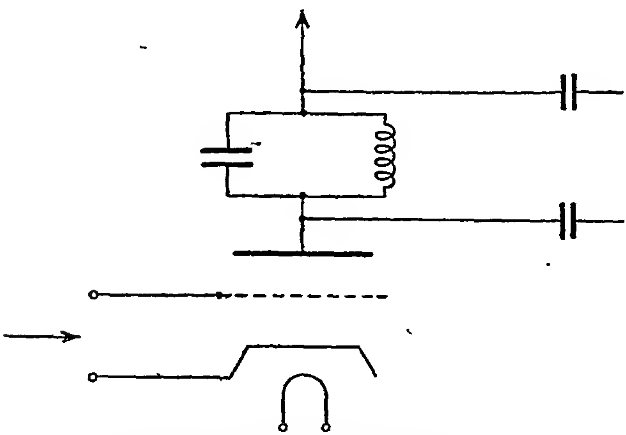


FIG. 191.—CIRCUIT FOR FREQUENCY DOUBLING. (Testing Circuit for Quality "Q").

through to the second grid, giving negative pressure to the plate of this valve and so round to the grid of valve 1.

The condensers charge, but the equilibrium is unstable and the circuit shoots off in the opposite direction. Bends in the valve curves must determine the amplitude.

Frequency Doubler or Trebler.

This is merely a valve with a tuned anode circuit, the anode being tuned to double or else three times the frequency put into the grid.

It is easy to see on the oscillograph when the circuit is in tune to the double frequency, especially if a double beam oscillograph is used.

Mains Power Units.

This makes a beautiful experiment when set up as shown in Fig. 192 (*a*).

The load resistance takes the place of the set and must get rid of the power, say $200 \times \cdot 1 = 20$ watts or more. The little resistance gives a voltage to work the oscillograph.

The various effects obtained are as follows:

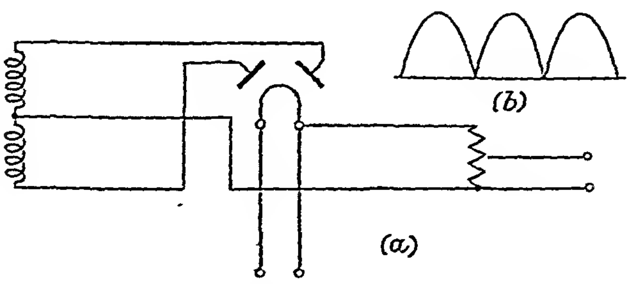


FIG. 192.—FULL WAVE RECTIFIER.

With one diode disconnected and left free, half wave rectification is obtained thus:

FIG. 193. HALF WAVE RECTIFIER.

When a choke is put in, but no condensers, thus:

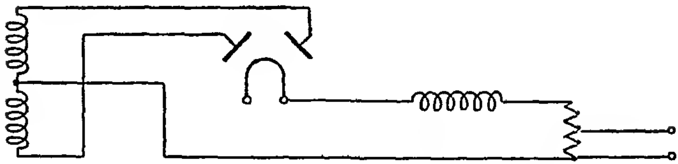


FIG. 194.—A CHOKE ONLY FOR SMOOTHING.

The ripple is reduced, but the high harmonics of Fig. 192 (*b*) which cause the sharp-points at the bottom are weakened more because *LW* is bigger when *f* is bigger; and so the wave is more like a sine wave.

A condenser only, gives a wave like that in Fig. 195.

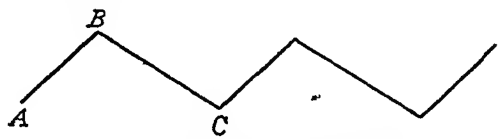


FIG. 195—FULL WAVE RECTIFIER.
Smoothing with a Condenser only.

The rise *A* to *B* is quick because it must be performed in a short time, namely the time of the peak of the *AC* wave. This is because the reservoir condenser *C*, always has some charge in it and some voltage. The diodes only add a current when the voltage is bigger than what is already in, and this can only be for a part of the cycle less than half.

The choke and condensers together give smoothing, but one can see (by turning up the amplifier on the oscillograph) that smoothing is a relative term. Indirectly heated valves are used for *AC* and the heaters are connected to a separate low voltage winding on the transformer—not the one heating the rectifier heater.

The Effects of Electric Current.

An excellent demonstration is described in *Electricity and Magnetism with Mechanics*, by J. M. Moir.

A current is taken through a lamp, a motor, a resistance for heat, along a wire suspended above a magnetic needle, and through a U-tube containing common salt in water with a little phenol-phthalein. This shows light, mechanical motion, heat, Oersted's experiment and chemical action all from the same current.

Eddy Currents.

The following experiment illustrates eddy currents very well, and was on view in Dr. E. W. Marchant's Laboratory at Liverpool University some years ago.

A bundle of Stalloy stampings, in a plain bar is wound with a coil of sufficiently heavy wire to give a powerful alternating field when a 50 cycle voltage is applied. The coil is contained

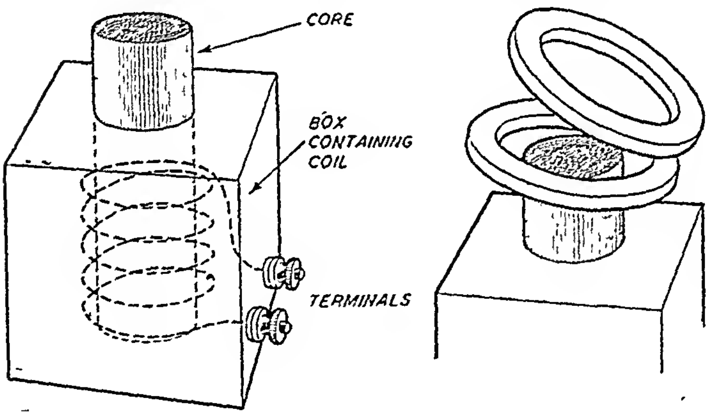


FIG. 196.—EXPERIMENT FOR DEMONSTRATING EDDY CURRENTS.

in a box and the core which is about 2 ins. diameter, projects above the coil for some inches as shown in Fig. 196.

One or two thick aluminium rings are made with an internal diameter of about $3\frac{1}{2}$ ins., and approximately 5/16 ins. thick. If these rings are slipped over the core before the current is switched on, they fly into the air when the switch is closed. This happens because the powerful eddy-currents generated in the rings are flowing in a direction which opposes

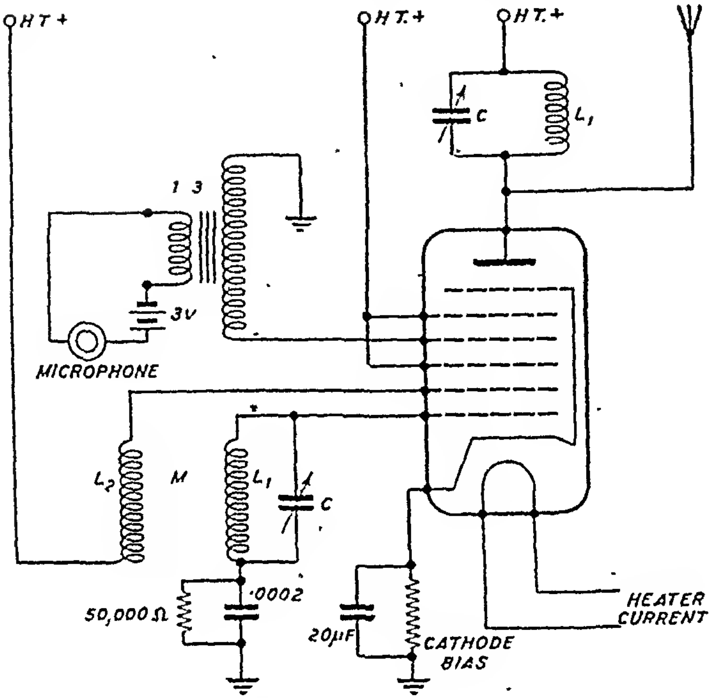


FIG. 197.—WIRING DIAGRAM OF SIMPLE BROADCAST TRANSMITTER.

the magnetic field of the coil which generates them. It is Lenz's Law.

A Simple Broadcast Transmitter.

A post office type microphone is coupled by transformer to an octode valve in which the oscillator section is oscillating at some medium wave frequency. A tuned anode circuit as shown in the theoretical wiring diagram (Fig. 197) is used, and a few feet of aerial wire is enough to radiate speech which can be picked up in another room on any domestic receiver.

INDEX